

Compendium of drinking-water systems and technologies from source to consumer



Compendium of drinking-water systems and technologies from source to consumer

Compendium of drinking-water systems and technologies from source to consumer

ISBN 978-92-4-011399-2 (electronic version)

ISBN 978-92-4-011400-5 (print version)

© World Health Organization 2025

Some rights reserved. This work is available under the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 IGO licence (CC BY-NC-SA 3.0 IGO; <https://creativecommons.org/licenses/by-nc-sa/3.0/igo>).

Under the terms of this licence, you may copy, redistribute and adapt the work for non-commercial purposes, provided the work is appropriately cited, as indicated below. In any use of this work, there should be no suggestion that WHO endorses any specific organization, products or services. The use of the WHO logo is not permitted. If you adapt the work, then you must license your work under the same or equivalent Creative Commons licence. If you create a translation of this work, you should add the following disclaimer along with the suggested citation: "This translation was not created by the World Health Organization (WHO). WHO is not responsible for the content or accuracy of this translation. The original English edition shall be the binding and authentic edition".

Any mediation relating to disputes arising under the licence shall be conducted in accordance with the mediation rules of the World Intellectual Property Organization (<http://www.wipo.int/amc/en/mediation/rules/>).

Suggested citation. Compendium of drinking-water systems and technologies from source to consumer. Geneva: World Health Organization; 2025. Licence: CC BY-NC-SA 3.0 IGO.

Cataloguing-in-Publication (CIP) data. CIP data are available at <https://iris.who.int/>.

Sales, rights and licensing. To purchase WHO publications, see <https://www.who.int/publications/book-orders>. To submit requests for commercial use and queries on rights and licensing, see <https://www.who.int/copyright>.

Third-party materials. If you wish to reuse material from this work that is attributed to a third party, such as tables, figures or images, it is your responsibility to determine whether permission is needed for that reuse and to obtain permission from the copyright holder. The risk of claims resulting from infringement of any third-party-owned component in the work rests solely with the user.

General disclaimers. The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of WHO concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. Dotted and dashed lines on maps represent approximate border lines for which there may not yet be full agreement.

The mention of specific companies or of certain manufacturers' products does not imply that they are endorsed or recommended by WHO in preference to others of a similar nature that are not mentioned. Errors and omissions excepted, the names of proprietary products are distinguished by initial capital letters.

All reasonable precautions have been taken by WHO to verify the information contained in this publication. However, the published material is being distributed without warranty of any kind, either expressed or implied. The responsibility for the interpretation and use of the material lies with the reader. In no event shall WHO be liable for damages arising from its use.

Design and layout by Michael Vock, fischbachervock.ch.

Illustration on the cover page and page xvi by Sandra Gujer, illuhouse.ch.

Contents

Acknowledgements	iv
Acronyms	vi
Glossary	vii
Introduction	1
Part 1 System templates	3
System 1 Rainwater harvesting	6
System 2 Centralized surface water treatment	8
System 3 Decentralized surface water treatment	12
System 4 Freshwater sources: manual transport combined with household water treatment and safe storage	16
System 5 Gravity flow supplies	18
System 6 High-quality groundwater	20
System 7 Groundwater subjected to geogenic contamination	22
System 8 Freshwater sources subjected to anthropogenic contamination	26
System 9 Desalination of brackish and salt water	28
Part 2 Technology information sheets	31
Source	32
S.1 Rainwater	34
S.2 Groundwater	36
S.3 Spring water	38
S.4 Rivers and streams	40
S.5 Ponds, lakes, and reservoirs	42
S.6 Brackish water, seawater	44
Intake	47
I.1 Roof water collection system	48
I.2 Rainwater catchment dam	50
I.3 Sand/subsurface storage dam	52
I.4 Protected spring intake	54
I.5 Protected dug well	56
I.6 Protected borehole	58
I.7 River and lake water intake	60
I.8 Riverbank filtration	62
I.9 Seawater intake	64
Abstraction	66
A.1 Hydraulic ram pump	68
A.2 Piston/plunger suction pump	70
A.3 Direct action pump	72
A.4 Piston pump; deep well pump	74
A.5 Progressive cavity pump; helical rotor pump	76
A.6 Diaphragm pump	78

A.7	Rope and washer pump	80
A.8	Radial flow pump	82
A.9	Axial flow pump	84
A.10	Gravity	86
A.11	Human powered	88
A.12	Wind	90
A.13	Solar	92
A.14	Electric	94
A.15	Internal combustion engine – diesel and petrol	96
Treatment		99
T.1	Clarification	
T.1.1	Roughing filtration	100
T.1.2	Rapid sand filtration	102
T.1.3	Microfiltration	104
T.1.4	Coagulation/flocculation/sedimentation	106
T.1.5	Coagulation/flocculation/filtration	108
T.2	Removal/inactivation of microorganisms	
T.2.1	Chlorination	110
T.2.2	On-site electrochlorination	112
T.2.3	Ultraviolet (UV) light disinfection	114
T.2.4	Slow sand filtration	116
T.2.5	Ultrafiltration	118
T.2.6	Pasteurization	120
T.3	Treatments for geogenic contaminants	
T.3.1	Fluoride removal methods	122
T.3.2	Arsenic removal methods	124
T.4	Treatments for organic and inorganic contaminants	
T.4.1	Activated carbon	126
T.4.2	Ozonation	128
T.4.3	Nanofiltration	130
T.5	Desalination	
T.5.1	Membrane distillation	132
T.5.2	Reverse osmosis	134
Distribution and transport		136
D.1	Jerry cans	138
D.2	Water vendors (carts and trucks)	140
D.3	Water kiosk	142
D.4	Small public and community distribution systems	144
D.5	Centralized distribution systems	146
D.6	Storage tanks or reservoirs	148
Household water treatment and safe storage		150
H.1	Storage tanks or reservoirs	152
H.2	Ceramic filtration	154
H.3	Ultrafiltration	156
H.4	Chemical disinfection	158

H.5 Boiling	160
H.6 Pasteurization	162
H.7 Biosand filtration	164
H.8 Ultraviolet (UV) light disinfection	166
H.9 Solar water disinfection	168
H.10 Fluoride removal filters	170
H.11 Arsenic removal filters	172

Part 3 | Cross-cutting issues **175**

Project planning and implementation	
X.1 Management typologies	176
X.2 Gender and inclusion	178
X.3 Life-cycle and environmental impact assessment	180
Assessing and managing risks	
X.4 Risk assessment and risk management	182
X.5 Water safety planning	184
X.6 Sanitary inspection	188
X.7 Quantitative microbial risk assessment	190
Monitoring and service sustainability	
X.8 Drinking-water quality regulation	192
X.9 Water quality monitoring	194
X.10 Data flow and information and communication technology (ICT)	196
X.11 External support programmes	198
X.12 Strengthening resilience to climate change	200

References and further reading **204**

Annex 1 Approach to content development and declarations of interest	226
Annex 2 Summary of select intake and treatment interventions to support safe drinking-water supply management	227

Acknowledgements

The World Health Organization (WHO) expresses its deep appreciation to all whose efforts made this publication possible by devoting their expertise, including the colleagues named below.

Development, technical editing and production of this publication were coordinated and managed by:

- **Maryna Peter** | University of Applied Sciences and Arts Northwestern Switzerland (FHNW), Switzerland
- **Sara Marks** | Swiss Federal Institute of Aquatic Science and Technology (Eawag), Switzerland
- **Lena Breitenmoser** | FHNW, Switzerland
- **Rory Moses McKeown** | WHO, Switzerland.

Contributors to the publication who provided text, peer review, additional insights, and/or participated in meetings include the following:

- **Benedikt Aumeier** | formerly of RWTH Aachen University, Germany
- **Antonio Barona** | formerly of VERTECH Group, France
- **Michael Berg** | Eawag, Switzerland
- **Anja Bretzler** | formerly of Eawag, Switzerland
- **Erasmus Cadena** | formerly of VERTECH Group, France
- **Valérie Cavin** | Helvetas Swiss Intercooperation, Switzerland
- **Guillaume Clair-Caliot** | formerly of Eawag, Switzerland
- **Arno Coerver** | Malteser International, Germany
- **David Cunliffe** | SA Health, Australia
- **Jennifer De France** | WHO, Switzerland
- **Elizabeth Engebretson** | WHO, Switzerland
- **Lorenz Ewers** | Arche noVa, Germany
- **Giuliana Ferrero** | formerly of IHE Delft Institute for Water Education, Netherlands (Kingdom of the)
- **Eric Fewster** | formerly of BushProof, Madagascar
- **Michael Fisher** | University of North Carolina, the USA
- **Declan Galbraith** | Arche noVa, Germany
- **Robert Gensch** | German Toilet Organization, Germany
- **Franziska Genter** | University of Technology Sydney, Australia
- **Jim Gibson** | consultant, South Africa
- **Moritz Gold** | formerly of Eawag, Switzerland
- **Bruce Gordon** | WHO, Switzerland
- **Fiona Gore** | WHO, Switzerland
- **Ulrich Gromke** | German Environment Agency, Germany
- **Stephan Hug** | formerly of Eawag, Switzerland
- **Alejandro Iriburo** | Obras Sanitarias del Estado, Uruguay
- **Rick Johnston** | WHO, Switzerland
- **Tim Julian** | Eawag, Switzerland
- **Georgia Kayser** | University of California San Diego, the USA
- **Christian Kazner** | formerly of FHNW, Switzerland
- **Ranjiv Khush** | Aquaya Institute, the USA
- **Richard King** | formerly of University of Surrey, United Kingdom of Great Britain and Northern Ireland
- **Emily Kumpel** | University of Massachusetts-Amherst, the USA
- **Karl Linden** | University of Colorado Boulder, the USA
- **Christoph Lüthi** | Eawag, Switzerland
- **Bonifacio Magtibay** | WHO, Philippines
- **Batsirai Majuru** | WHO, Switzerland
- **Jay Matta** | formerly of United Nations High Commissioner for Refugees, Switzerland
- **Regula Meierhofer** | Eawag, Switzerland
- **Adeline Mercenat** | Eawag, Switzerland
- **Ellen Milnes** | University of Neuchatel, Switzerland
- **Maggie Montgomery** | WHO, Switzerland
- **Eberhard Morgenroth** | Eawag, Switzerland
- **Alois Müller** | University of Applied Sciences Bern, Switzerland
- **Sofia Murad** | WHO, Switzerland
- **Abishek Narayan** | Eawag, Switzerland
- **Emmanuel Ortle** | formerly of FHNW, Switzerland
- **Rachel Peletz** | Aquaya Institute, the USA
- **Fabian Peter** | AquaPlus, Switzerland
- **Susan Petterson** | Water and Health, Australia
- **Nadja Rastetter** | formerly of FHNW, Switzerland
- **Bettina Rickert** | German Environment Agency, Germany
- **Angella Rinehold** | WHO, Switzerland
- **Javier Royo Abancéns** | formerly of Solintel, Spain
- **Eduard Sandyk** | German Environment Agency, Germany
- **Caroline Saul** | Eawag, Switzerland
- **Ariane Schertenleib** | formerly of Eawag, Switzerland
- **Karen Setty** | formerly of University of North Carolina, the USA
- **David Sheehan** | Coliban Water, Australia
- **Kari Sholtes** | Colorado Mesa University, the USA
- **Patrick Smeets** | KWR, Netherlands (Kingdom of the)
- **Stef Smits** | IRC, Netherlands (Kingdom of the)
- **Gabriele String** | Tufts University, the USA
- **R Scott Summers** | University of Colorado Boulder, the USA
- **Mark Summerton** | formerly of United Nations Children's Fund, Jordan
- **Elizabeth Tilley** | ETH Zurich, Switzerland

- Michael Thomann | FHNW, Switzerland
- Sital Uprety | formerly of Eawag, Switzerland
- Emily van Houweling | Regis University, the USA
- Saravanamuth Vigneswaran | University of Technology Sydney, Australia
- Urs von Gunten | Ecole Polytechnique Fédérale de Lausanne, Switzerland
- Barbara J. Ward | formerly of Eawag, Switzerland
- Sujithra Weragoda | Ministry of Water Supply, Sri Lanka
- Juliet Willetts | University of Technology Sydney, Australia
- Thomas Wintgens | RWTH Aachen University, Germany
- Robin Wünsch | formerly of FHNW, Switzerland
- Christian Zurbrügg | Eawag, Switzerland

Karl Linden, University of Colorado Boulder, the USA, is also acknowledged for his contribution to the development of Annex 2.

The financial support provided by the following agencies is gratefully acknowledged: Agence Française de Développement, France; the Australian Government Department of Foreign Affairs and Trade, Australia; the Directorate General for International Cooperation, Netherlands (Kingdom of the); the Foreign, Commonwealth and Development Office, the United Kingdom; the Ministry of Development Cooperation and Humanitarian Affairs, Luxembourg; the Ministry of the Environment and Water Resources, Singapore; the Ministry of Health, Labour and Welfare, Japan; the Norwegian Agency for Development Cooperation, Norway; and the Swiss Agency for Development Cooperation, Switzerland.

Acronyms

AC	alternating current	P/A	presence/absence
AC	activated carbon	PET	polyethylene terephthalate
As	arsenic	PP	polypropylene
		PV	photovoltaic
BSF	biosand filter	PVC	polyvinyl chloride
CDC	Centre for Disease Control	QMRA	quantitative microbial risk assessment
CFU	colony forming unit		
CIP	clean in place	RNA	ribonucleic acid
COD	chemical oxygen demand	RO	reverse osmosis
DC	direct current	SDG	Sustainable Development Goal
DFD	data flow diagram	SI	sanitary inspection
DNA	deoxyribonucleic acid	SKAT	Swiss Centre for Development Cooperation in Technology and Management
<i>E. coli</i>	<i>Escherichia coli</i>	SODIS	solar disinfection
EBCT	empty bed contact time	SPPS	solar-powered pumping systems
ESP	external support programme		
		TDS	total dissolved solids
F	fluoride		
FAO	Food and Agriculture Organization	UF	ultrafiltration
		UN	United Nations
GAC	granular activated carbon	UNDP	United Nations Development Programme
GIS	geographic information system	uPVC	unplasticized polyvinyl chloride
GPS	global positioning system	UV	ultraviolet
		UVT	ultraviolet transmittance
HDPE	high density polyethylene		
HTH	high test hypochlorite	VFD	variable-frequency drive
ICT	Information and communications technology	WHO	World Health Organization
IRC	International Reference Centre	WSP	water safety plan
ISO	International Organization for Standardization		
IUCN	International Union for Conservation of Nature		
LCA	life-cycle assessment		
LCI	life-cycle inventory		
LCIA	life-cycle impact assessment		
LED	light-emitting diode		
LRV	log reduction value		
MD	membrane distillation		
MF	microfiltration		
MPN	most probable number		
NA	not applicable		
NF	nanofiltration		
NGO	non-governmental organization		
NPSH	net positive suction head		
NTU	nephelometric turbidity unit		

Glossary

A

Abstraction: Removal of water from a source.

Acidity: Higher concentration of positive hydrogen ions in the solution, resulting in a low pH value (below pH 7).

Adsorption: Adhesion of a thin film of liquid, vapour or dissolved ions to a solid substance without involving a chemical reaction.

Alkalinity: Capacity of water to resist or neutralize acids to maintain a stable pH level.

Alluvial: Loose unconsolidated material (i.e. particles are not cemented together) that was previously deposited by ice or flowing water.

Aquifer: Geological formation capable of storing, transmitting (flow rate) and yielding exploitable quantities of water.

B

Backfilling: Filling a hole using some of the material that was removed during the digging or drilling process.

Backwashing: Reversal of the flow of water to free a clogging material (e.g. sediments within a rapid sand filter or reverse osmosis filtration cartridges).

Biological contaminants: Organisms in water also referred to as microbes or microbiological contaminants (e.g. bacteria, viruses, protozoa) (syn.: microbial/microbiological contaminants).

Bone char: Porous granular substance used for water filtration and decoloration; produced by charring animal bones.

Borehole: A narrow shaft bored or drilled from the surface to underground water sources for the extraction of water.

Brackish water: Water with more salinity than fresh water but less than seawater (1000–10000 mg/L total dissolved solids). It is usually the result of seawater intrusion into groundwater bodies along coastal areas.

Brine: Water with high salinity (e.g. from aqueous sodium chloride used in electrochlorination systems).

Buoyancy: Upward force exerted by water or fluids on objects that are wholly or partly immersed.

C

Canzee pump: An inexpensive direct-action hand pump that consists of two PVC pipes inside of each other, each with a simple non-return valve made with a rubber flap. Maximal water lifting capacity is 12–15 metres.

Capital costs: Costs related to the acquisition of a fixed asset or hardware.

Catchment: A surface area that collects and drains rainwater and snow melt to a certain point (e.g. a small-scale roof catchment drains water that falls on the roof or a large-scale ground catchment drains water from surrounding land).

Check valve: A valve that allows liquids or gas to flow through it only in one direction. Also known as a non-return valve.

Chemical contaminants: Elements or compounds in water that may be naturally occurring (e.g. fluoride, arsenic, nitrate, toxins produced by bacteria) or that arise from human activities (e.g. pesticides, heavy metals).

Chemical oxygen demand (COD): Measure of the amount of oxygen required for the chemical oxidation of organic material in water by a strong chemical oxidant (expressed in mg/L). COD is an indirect measure of the amount of organic material present in water – the higher the organic content, the higher the oxygen requirement.

Chlorination: The process of adding chlorine or chlorine compounds (e.g. sodium hypochlorite) to drinking-water to inactivate bacteria, viruses, and other microbes.

Chlorine decay: The decrease in chlorine concentration as water passes through a water supply system due to the reaction between chlorine and organic and/or inorganic materials.

Chlorine demand: The amount of chlorine added to water that is completely exhausted in the water disinfection process.

Chlorine contact time: The time of contact between chlorine and water for disinfection to occur.

Coagulation: Process in which a chemical (e.g. aluminium sulphate or ferric chloride) is added to water to destabilize electrostatic charges of colloids, allowing these smaller particles to come together to form larger particles (through flocculation), which settle out faster or can be filtered due to their larger size.

Colloids: Stable insoluble substances that are so small that the random motion of water molecules is sufficient to prevent them settling under gravity.

Compliance monitoring: Confirms compliance with drinking-water quality regulations, including verifying that the drinking-water supplied to users is safe.

Confined aquifer: A saturated geological formation in which the water pressure at any point is greater than atmospheric pressure.

Contaminant: Physical, chemical, biological, or radiological substance present in water that may be naturally occurring or arising from human activities and that may adversely affect public health.

Control measure: An activity or process to prevent, eliminate, or reduce the risk of a hazardous event to an acceptable level.

D

Desalination: The process of removing salts and minerals from water.

Desilting: The process of removing silt or deposits from a tank or reservoir.

Dewatering: The process of removing water (e.g. pumping water from an excavation).

Diffused sources of contamination: Contamination coming from unspecific (non-point) pollution sources over a wide area (e.g. pollution from agriculture).

Discharge: The volume of water that passes a given point within a given period of time. It is an all-inclusive outflow term describing a variety of flows, such as from pipes or streams.

Disinfection: The elimination of pathogenic micro-organisms by inactivation (e.g. using chemical agents, radiation or heat) or by physical separation processes (e.g. membranes).

Disinfection by-products: Chemical, organic, and inorganic substances that result from a reaction of a disinfectant (e.g. chlorine or chlorine compounds) with naturally occurring organic matter in water and long-term exposure to these compounds may result in health concerns.

Downstream: Further away from the source; the direction in which water is naturally flowing.

Duty pump: The pump in use most of the time (i.e. not the standby pump).

E

Effluent: Outflow of water or another liquid from a pipe or treatment plant that is discharged to a stream or body of water.

Electrolysis: A technique using a direct electrical current to drive an otherwise nonspontaneous chemical reaction.

Erosion: The process by which soil and rock are worn away, loosened or dissolved and moved by natural forces such as rain, snow or wind.

Evaporation: The process by which water turns from its liquid phase into gas (vapour).

Evapotranspiration: The process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.

F

First flush: The initial and often sediment- and contaminant-laden surface runoff in rainwater harvesting systems that is diverted away from the storage tank.

Flocculant: Clarifying agents used in water treatment to remove suspended solids from liquids by inducing flocculation.

Flocculation: A physical process wherein particles come together to form larger particles (flocs) following the introduction of floc-creating agents (flocculants) and slow agitation of the water.

Flywheel: A mechanical device designed to efficiently store rotational kinetic energy, giving mechanical advantage to lifting water.

Free chlorine residual: The amount of active (free) chlorine remaining in the water after a certain period of time (e.g. 30 minutes of contact time) when the initial chlorine demand has been met (syn.: residual chlorine).

Friction loss: Reduction in energy that occurs when water moves due to water molecules knocking into each other and against the pipe wall, which converts some of the total available energy into heat that dissipates into the environment (syn.: head loss).

G

Generator: A machine that uses fuel (e.g. diesel) to convert mechanical energy into electricity.

Gravity: The force that attracts an object or substance towards the centre of the earth or towards any other physical body having mass.

Greywater: Water generated from showers, bathtubs, washing clothes, hand-washing and sinks.

Groundwater: Water that is held in pores and spaces within the geological formations of the earth's surface.

Groundwater recharge: Process wherein groundwater is replenished. To be sustainable, this should be equal to or greater than what is abstracted.

Groundwater table: The surface of the saturated water-bearing layer in the ground that is open to atmospheric pressure and that is not static but can vary over time due to lower recharge or higher usage.

H

Hazard: A contaminant or condition that may adversely affect the supply of safe drinking-water.

Hazardous event: An event that results in a hazard being introduced to, or inadequately removed from, the water supply.

Head loss: See friction loss (syn.).

Headwall: A wall of masonry or concrete built at the outlet of a pipe that functions to support the sides of an excavation as well as (together with the apron) to prevent erosion by water flow.

Heavy metals: Metals with relatively high density that can enter water supply systems either through artificial sources (e.g. industrial or consumer waste) or natural sources (e.g. released from soils) and that can pose potential health risks.

Helical rotor pump: A positive displacement pump that works through the rotation of a helical rotor, which is shaped as a single helix that sits within a stationary double-helix rubber stator. Water occupies the cavity between the two, and when the rotor turns, this cavity moves upwards together with the water (syn.: progressive cavity pump).

Hydraulic cleaning: A set of techniques to clean pipes and sewer lines that includes the use of high-pressure and high-velocity water.

Hydraulic conductivity: A property of soils and rocks that describes the ease with which a fluid (in this case water) can move through pore spaces or fractures.

Hydraulic gradient: A measure of the decrease in total energy per unit length in the direction of flow when water is moving, which results from the phenomenon known as head loss.

Hydrogeological survey: An investigation of geology, groundwater, geochemistry, and contamination at a particular site, as well as climatic and recharge conditions, with a view to understanding the risk to groundwater and/or the potential for groundwater to be supplied in a sustainable manner.

I

Impeller: A rotating component of a centrifugal pump that accelerates the fluid outwards from the centre of rotation.

Improvement plan: Groups priority actions identified to progressively improve management and safety of the supply, including proposed timelines and needed resources.

Impulse pump: A pump using pressure created by air that pushes part of the liquid upwards.

In situ: On site or in position.

Incident/near-miss: Event where loss of control has led to (or narrowly missed) a public health risk.

Industrial effluent: By-product of industrial or commercial activities, often with high physical and chemical contamination.

Infiltration: Process by which water on the ground surface enters into the soil.

Inflow: Flow of water into a specific technology.

Inlet: A part of a machine or structure through which liquid or gas enters.

Inorganic: Material derived from non-living sources (such as rock or minerals) and that does not contain carbon.

Intake: An opening through which fluid enters an enclosure (e.g. river intake) or a machine (e.g. pump intake, same as pump inlet).

Integrated water resources management (IWRM): A process that promotes the coordinated development and management of water, land and related resources to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

Ion exchange: Process by which an ion in a mineral lattice is replaced by an ion from a contacting solution.

J

Jar test: A laboratory procedure that simulates a chemical treatment process on smaller quantities of water using differing chemical doses. Applied to optimize the removal of colloids during water treatment.

K

Kinetic energy: Form of energy that an object has due to its motion.

L

Log reduction value (LRV): A logarithmic measure of the ability of a treatment process to remove pathogenic microorganisms. An LRV of 1 corresponds to a reduction of 90%, an LRV of 2 corresponds to a reduction of 99%, etc.

M

Managed aquifer recharge (MAR): The intentional recharge of water to suitable aquifers for subsequent recovery or to achieve environmental benefits, with added effects of reducing poverty, reducing risk and vulnerability, and increasing agricultural yields.

Membrane: A thin, pliable sheet or layer of natural or synthetic (filter) material.

Membrane fouling: Material retained on the surface of the membrane or within the pores that reduces the flow through the membrane.

Micropollutants: A pollutant, usually from an artificial source, that is present in extremely low concentrations (e.g. trace organic compounds) that may adversely impact health.

Microbial/microbiological contaminants: See biological contaminants (syn.).

Mitigation: The process or result of making something less severe, dangerous, or damaging.

N

Nephelometric turbidity units (NTU): Measure of how much light shines through a water sample and reaches a detector on the other side of the sample. Particles in the water reflect more light sideways, meaning more light arrives at the detector. A higher turbidity results in a higher NTU reading.

O

Operation and maintenance (O & M): Routine or periodic tasks required to keep a process or system functioning according to performance requirements and to prevent delays, repairs or downtime, or adverse impacts on the safety of the water supply.

Operational costs: The expenses associated with the operation, maintenance and administration of a specific technology or system.

Operational monitoring: Routine monitoring performed to ensure that control measures are working to protect water safety at key steps along the water supply chain and inform operational decisions.

Organic: Material containing carbon-based compounds coming from the remains of organisms such as plants and animals (and their waste products).

Outflow: Flow of water coming out of a specific technology.

Outlet: A part of a machine or structure through which liquid or gas exits.

Oxidation: The loss of electrons during a reaction by a molecule, atom or ion, e.g. when iron reacts with oxygen, it forms rust because it has been oxidised (the iron has lost electrons) while the oxygen has been reduced (the oxygen has gained electrons).

P

Pathogen: A disease-causing organism.

Permeability: The soil's hydraulic conductivity after the effect of fluid viscosity and density are removed (i.e. describes the innate properties of the soils and rocks themselves).

Permeate: To diffuse through; to pass through the pores or interstices of something.

Personal protective equipment (PPE): Protective equipment (e.g. clothing, helmets, or goggles) designed to protect the wearer from injury or infection.

pH: Stands for “potential of hydrogen” (or “power of hydrogen”); a logarithmic scale used to specify the acidity or basicity of an aqueous solution. A pH value below 7 indicates that a solution is acidic, and a pH value above 7 indicates that it is basic (alkaline).

Piston: The moving component of reciprocating pumps (among others) that is tightly contained within a cylinder.

Point of collection (POC): Location where water is collected by users (e.g. borehole, tapstand, river or lake).

Point of use (POU): Location where the water is actually used and consumed (usually directly at household level).

Point source of contamination: Contamination coming from a specific pollution source that can be specifically located.

Positive displacement pump: A pump that displaces a fixed amount of water per cycle.

Porosity: Ratio of the volume of interstices (intervening spaces) in a given sample of a porous medium to the gross volume of the sample, inclusive of voids.

Precipitation: Condensation of atmospheric water vapour that returns to the earth’s surface as rain, snow, hail or fog.

Progressive cavity pump: See helical rotor pump (syn.).

Protected spring: A spring that is modified to collect, transport and sometimes store spring water while preventing contamination.

Pump discharge: The water coming out of a pump or the outlet port of a pump.

Pumping test: A field test in which the performance of an aquifer is measured through the action of pumping a well to demonstrate well efficiency, possible yield and pump placement.

R

Rainwater: Water from liquid precipitation.

Recharge: Refers to water entering an underground aquifer through faults, fractures, or direct absorption.

Recontamination: The process of treated water becoming contaminated again (e.g. water that was disinfected at water system level becomes recontaminated with microorganisms during transport to or handling in the home).

Rehabilitation: The restoration of something damaged or deteriorated to a prior good condition.

Reservoir: An impoundment of surface water in a natural depression that has been enhanced to hold the water by a human-made structure on one or more sides.

Residual pressure: The extra pressure above a tap or outlet that is equal to either the static head (when no water flows) or to a point on the hydraulic gradient (when water flows).

Resuspension: The renewed suspension of a precipitated sediment (e.g. when stirring up mud that has settled at the bottom of a tank).

Rising main: A pipe from a submerged part of a pump that rises to where water is delivered (e.g. pump head for a hand pump or water tank for a submersible pump).

Risk: The product of the likelihood of occurrence of a hazardous event and its severity (or consequences).

Riverbed: The bed or channel through which water flows, which is located at a lower point in a drainage system.

Run-off: Water from precipitation that runs off the ground surface (rather than infiltrating), which then enters rivers, lakes or reservoirs.

Run-off coefficient: The percentage of water that runs off a surface and can be collected, wherein the remainder is lost (e.g. to splashing, evaporation or infiltration).

S

Saline/salty water: Water that has a high content of dissolved solids and is generally considered unsuitable for human consumption.

Saltwater intrusion: The movement of saline water into freshwater aquifers that can degrade groundwater quality (see also brackish water).

Salinity: The quality or degree of dissolved salt content.

Sand trap: A plain section of casing under the screens at the bottom of a borehole that allows fine silt/sand par-

ticles to accumulate during the well development process and over time.

Saturation: When all the pores of a material or medium (e.g. soil) are filled with water.

Schmutzdecke: The most biologically active part of a slow sand filter, consisting of a dense population of microorganisms that develops over time and that is key to the disinfection properties of the filter (syn.: biolayer).

Screen: A device used to prevent objects or particles from entering the water supply. Common examples of screens used in water supply operations include slotted pipes in boreholes or a set of bars used in raw water intakes (syn.: well screen).

Sedimentation: The settling out of particles in a liquid by force of gravity.

Seepage: The slow escape of liquid (e.g. water from a diffuse spring).

Silt trap: A device to prevent silt from entering a tank or water treatment system.

Siltation: The deposition of fine sediment in the bottom of a stream, lake or reservoir.

Solubilisation: Process by which a substance is made (more) soluble in water.

Strainer: A device with holes or made of crossed wires that is used to separate solid matter from a liquid. For surface water pumps, it is used at the end of the inlet pipe to prevent larger materials from entering the pipe.

Submersible pump: A pump that is located underwater, from where it pushes water. It has a hermetically sealed motor that is close-coupled to the pump body.

Suction pump: A pump that is located above the water surface, from where it pulls water by suction into the pump housing.

Surface water: Water that remains on the ground surface in large bodies (e.g. streams, lakes, wetlands) and that has not infiltrated into the ground.

Supporting programmes: Actions that contribute to drinking-water safety but do not directly affect water quality.

Suspended solids: Small solid particles that remain in suspension in water either as colloids or due to the motion of the water.

Siphon: A pipe or tube in an inverted U-shape used to convey liquid (under the pull of gravity) upwards above the surface of a reservoir and then down to a lower level, with water discharging at a level below the surface of the reservoir.

T

Tankering/trucking: The bulk transport of water using a water tanker vehicle, which takes water from the source to a storage facility near a distribution point (syn.: water carting).

Tara pump: A low-cost and robust direct action hand pump with a buoyant pump rod that displaces water on both the up and down strokes. Maximal water lifting capacity is 15 metres.

Topography: The shape and features of land surfaces.

Totally dissolved solids (TDS): The quantity of minerals (salts) in solution in water, usually expressed in milligrams per litre (mg/L) or parts per million (ppm).

Turbidity: The measure of relative clarity of a liquid, usually expressed in nephelometric turbidity units (NTU).

Turbine: A machine for producing continuous power in which a wheel or rotor, typically fitted with vanes, is made to revolve by a fast-moving flow of water, steam, gas, air or other fluid.

U

Ultraviolet (UV) light: Type of electromagnetic radiation that disinfects water through the inactivation of pathogenic microorganisms.

Unconfined aquifer: A saturated geological formation that is open to atmospheric pressure; its surface is known as the groundwater table.

Underdrain: A concealed drainage area/trench that allows water to pass while retaining material on top (e.g. a drainage area at the bottom of a rapid sand filter).

Unprotected spring: A spring that is in its natural state and has not been modified to prevent contamination.

Upflow filtration: Filtration process in which water flows from bottom to top.

Upstream: Nearer to the source; against the direction in which water is naturally flowing.

V

Velocity: Speed, or how far something travels over time.

Verification (as part of water safety planning): The process of obtaining evidence that a water safety plan, as a whole, is working effectively to deliver safe drinking-water.

W

Water column: Conceptual column describing the vertical expanse of water between the surface and the bottom of a particular water body.

Water hardness: A water quality parameter that indicates the amount of dissolved minerals, especially calcium and magnesium. Hard water has higher levels of these minerals.

Water metering: The practice of measuring the amount/volume of water used over time.

Water safety plan (WSP) / Water safety planning: A proactive risk assessment and risk management approach to safeguard public health, encompassing the whole drinking-water supply system from catchment to consumer.

Water tariff: The price assigned to water supplied by a public utility (usually through a piped network) to its customers.

Well: Any artificial excavation constructed for the purposes of exploring and extracting groundwater or for injection, monitoring or de-watering purposes.

Well efficiency: The ratio of aquifer loss (theoretical drawdown) to the total measured drawdown in a borehole/well, which shows the efficiency of the well as an engineering structure for water abstraction.

Well screen: See screen (syn.).

Y

Yield: The amount of water that can be abstracted over time.



Introduction

The World Health Organization's (WHO) *Guidelines for drinking-water quality* (the Guidelines) recommend the implementation of a "Framework for safe drinking-water" as the basic and essential requirement to assure the safety of water supplies (WHO, 2022a). This framework comprises drinking-water quality targets (established by a competent health authority), adequate and properly managed drinking-water systems to achieve these targets, and independent surveillance.

Ensuring the adequacy and safety of drinking-water requires not only adequate infrastructure, but effective planning and management. Water safety planning is a comprehensive risk assessment and management approach encompassing all steps in a water supply system. Water safety planning principles should be applied by all water suppliers to ensure adequate and safe drinking-water supply (WHO, 2022a). In addition to drinking-water quality considerations, water safety planning also helps to ensure there is a sufficient quantity of water for household use (including for drinking, food preparation and hygiene) to protect public health and for well-being and prosperity (WHO, 2020; WHO, 2022a).

The WHO Guidelines do not prescribe specific water supply systems or technologies. Rather, they recognize that drinking-water quality targets for microbial pathogens and chemical and radiological parameters can be achieved through a variety of different supply and treatment approaches. Such approaches should be selected for the local context, with effective management and oversight to ensure an adequate supply of safe drinking-water.

The *Compendium of drinking-water systems and technologies from source to consumer* (the Compendium) brings together a concise overview of drinking-water systems and technologies with a global focus. It provides foundational knowledge to support readers to make informed decisions with regards to the selection of context appropriate drinking-water systems and technologies, towards the achievement of the recommendations outlined by WHO.

The Compendium also supports the implementation of the guidance within the *Guidelines for drinking-water quality: small water supplies* (WHO, 2024a), providing practical information to inform technological interventions for safe drinking-water management, and technology-related aspects of drinking-water quality regulations.

The Compendium is a companion publication to *Compendium of water supply technologies in emergencies* (Coerver et al., 2021). Both publications have a shared history of development, diverging where required for their distinct target audiences and application contexts. Both compendia originated from a public European Union Water4India project report developed

by FHNW and project partners (Breitenmoser, Peters & Kazner, 2016), from which selected technology information sheets were adapted for both publications with the permission of authors.

The development methodology for the Compendium is detailed in Annex 1.

Target audience and objectives

The Compendium targets engineers, planners, and practitioners, including local decision-makers and implementers as well as local and international experts of non-governmental organizations.

This publication provides an overview of the available drinking-water systems and possible configurations, and is not meant to be used as a single source of information for the design and implementation of a technology or a system. It can be used for communicating planning processes for water supply systems based on the local needs and resource availability in low- and middle-income countries. This includes small scale water treatment versus point-of-use and rural versus peri-urban or urban contexts.

Structure of the Compendium

The Compendium describes nine typical drinking-water supply schemes with differing water sources and water qualities (Part 1: System templates). The system template descriptions provide information about technological steps from water sources and water withdrawal technologies to household water treatment and storage. Each system template is disaggregated into their main components, namely:

- S. Source: all water sources
- I. Intake: water-intake structures used for withdrawing water from different sources
- A. Abstraction: water-abstraction technologies, used to withdraw water from the source through the chosen intake systems
- T. Treatment: water-treatment technologies used for both centralized and small scales
- D. Distribution and transport: means of distribution, transport, and storage of water
- H. Household water treatment and safe storage: household activities that may influence water safety, namely hygienic storage, handling, and household water treatment.

The second part of the Compendium (Part 2: Technology information sheets) provides concise information on the differing technologies available under each of the outlined components – the functional groups of a drinking-water supply system. A summary table of technological interventions is presented in Annex 2.

The third part of this document (Part 3: Cross-cutting issues) addresses aspects of the enabling environment, such as regulation and monitoring, recognizing the critical importance of an effective enabling environment to help ensure the sustainable delivery of safely managed drinking-water supplies. It also addresses other aspects relevant for planning and implementing water supplies, including risk management strategies, life-cycle assessment, gender and inclusion issues, external support, and strengthening resilience.

Part 1 | System templates

Drinking-water supply systems can be graphically presented as a matrix of functional groups (columns) that correspond to the different components of a supply system from source to consumer. These functional groups can be linked to show possible combinations. Colour-coded columns represent the six functional groups:

- **Source**
- **Intake**
- **Abstraction**
- **Treatment**
- **Distribution and transport**
- **Household water treatment and safe storage**

Water is abstracted from a water resource through an intake system and is delivered by gravity flow or pumping to the treatment facility where it is treated by a combination of technologies depending on the quality. Subsequently, treated water is delivered through a distribution network or transported by other means to consumers, whom can either use the water directly, store it safely, or further treat it. It is not always necessary that water passes through all functional groups to reach a consumer. For example, in some systems, treatment is excluded or limited due to high-quality source water or a lack of resources. Water could also be supplied by gravity such that no pumping is needed. Even if one is skipped, water always moves from left to right through the functional groups.

Steps for selecting technological options using system templates

The following nine system templates present common drinking-water supply systems based on the water source used. The drinking-water supply systems are as follows and are presented with the most logical combinations of technologies:

- System 1** Rainwater harvesting
- System 2** Centralized surface water treatment
- System 3** Decentralized surface water treatment
- System 4** Freshwater sources: manual transport combined with household water treatment and safe storage
- System 5** Gravity flow supplies
- System 6** High-quality groundwater
- System 7** Groundwater subjected to geogenic contamination
- System 8** Freshwater subjected to anthropogenic contamination
- System 9** Desalination of brackish and salt water

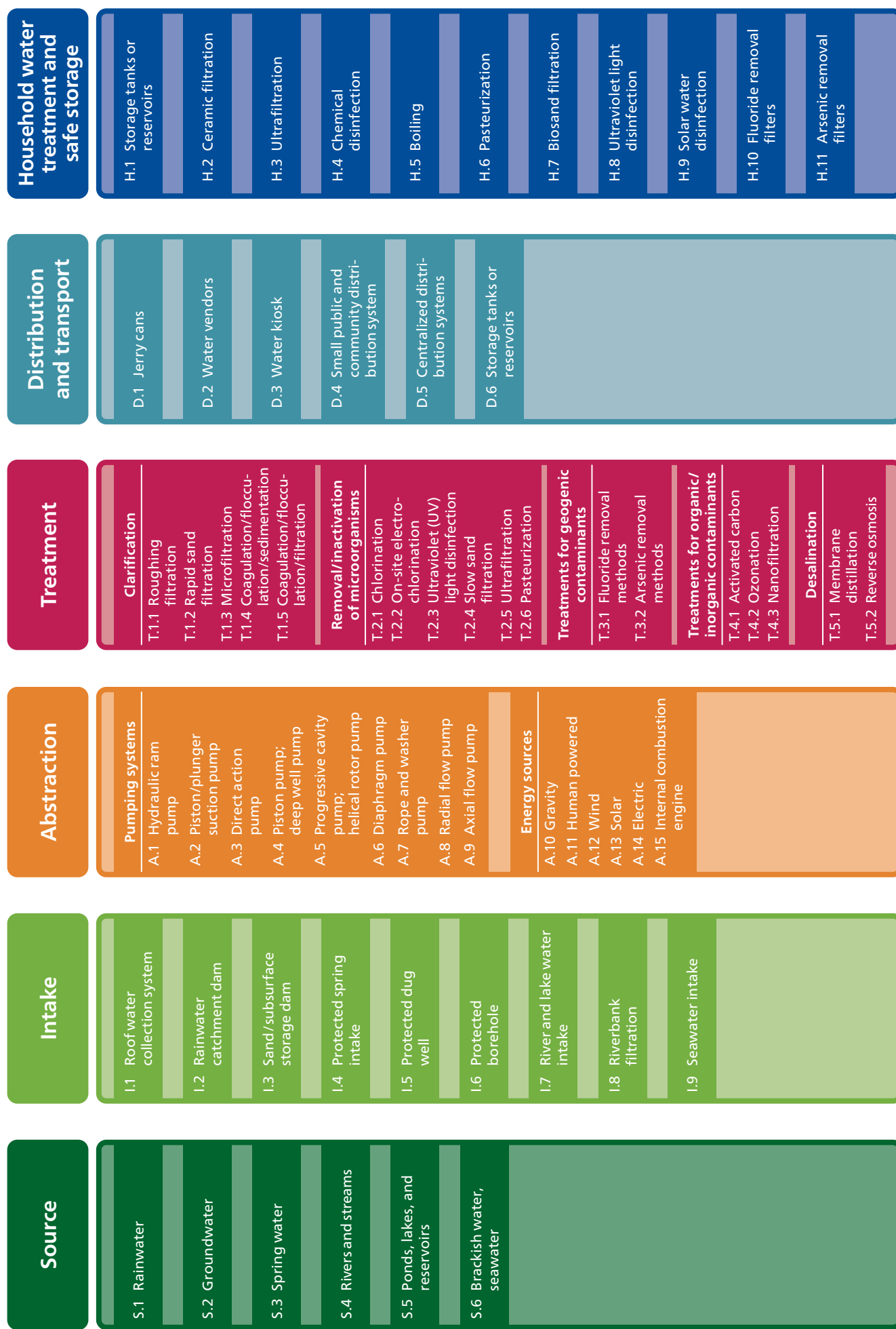
The technologies presented in the Compendium and the links between them are not exhaustive. Planners and designers should always try to make the best use of available resources and optimize or rehabilitate existing infrastructure while taking the local environment into account, including available capacities and skills, financial resources, regulations, and socio-cultural preferences and acceptance (see also Part 2 and Annex 2). The below steps can be followed to facilitate selection of appropriate water supply options:

1. Identify water resources that are available and accessible.
2. Identify system templates that include and address these water resources.
3. For each template, select a technology or multiple technologies from the boxes shown in each functional group. The series (following the arrows) of technologies make up a system.
4. Compare differing systems and iteratively change individual technologies or use different system templates based on considerations such as users' priorities, level of service, and resources available.

In some cases, it can be useful to carefully consider the geography of the area and divide it into sub-areas depending on the availability and location of water sources, population characteristics, and other environmental conditions. The procedure can be followed for each of the sub-areas, and several different systems can be chosen. Usually, there is an existing water source that can already be used and some infrastructure is available. It is always recommended to integrate existing infrastructure or services into the planning process, but one needs to be flexible enough to exclude it if drinking-water safety or acceptance is an issue.

The nine system templates are presented and described in detail on the following pages.

System template



System 1 Rainwater harvesting

This system can be used as a major source of water supply where there is sufficient rainfall and storage capacity. It can also be used seasonally to complement other water sources. This system template focuses on rainwater harvested from roofs or similar structures. Rainwater captured by surface or subsurface run-off systems is considered in System 3 Decentralized surface water treatment.

Rainwater (see S.1 Rainwater) is collected through a roof water collection system and diverted to storage tanks via guttering fixed with hooks below the roof to catch the run-off water. Guttering is available in different materials, such as PVC, zinc, copper, aluminum, ferro-cement, timber, or metal sheets. It should be installed with an even slope to avoid the formation of stagnant water pools where mosquitos can breed. The roof water collection system (see I.1 Roof water collection system) should optimally contain a first-flush mechanism to redirect and discharge the first portion of rainwater from the roof, which is the most likely to be contaminated. The capacity of the first-flush system should be designed relative to the size of the roof catchment area. The flushed water should be redirected away from the collection area (e.g. via a soak pit or drainage channel) and should not be used for human consumption. Some configurations may include a filter box upstream of the first-flush mechanism with a coarse filter to protect against larger pieces of debris entering the system. In some cases, rainwater is collected first into a settling tank and later redirected to a storage tank. Polyvinyl chloride (PVC), ferro-cement, or metal tanks can be placed above or below ground to collect and store rainwater. The required size of the storage tank is a function of the water supply and demand throughout the dry period, including unplanned use or use for other needs and the availability of alternative sources. It should be large enough to accommodate user needs during a defined period of time without rain.

The main design parameters of a roof water collection system are determined by rainfall quantity and pattern, roof catchment area, run-off coefficient, and water demand. The amount of rainwater harvested at a given time of the year can be estimated using the following equation:

$$\text{Supply (L/year)} = \text{Rainfall (mm/year)} \times \text{Roof area (m}^2\text{)} \times \text{Run-off coefficient}$$

The roof run-off coefficient is the ratio of the volume of rainwater that runs off the surface to the volume of rainwater that falls on that surface (typically varies

between 0.5–0.9). A run-off coefficient of 0.9 means that 90% of the rainfall is collected. It considers water losses due to factors that include spilling, evaporation, wind, overflowing gutters, leaky collection pipes, and first-flush devices.

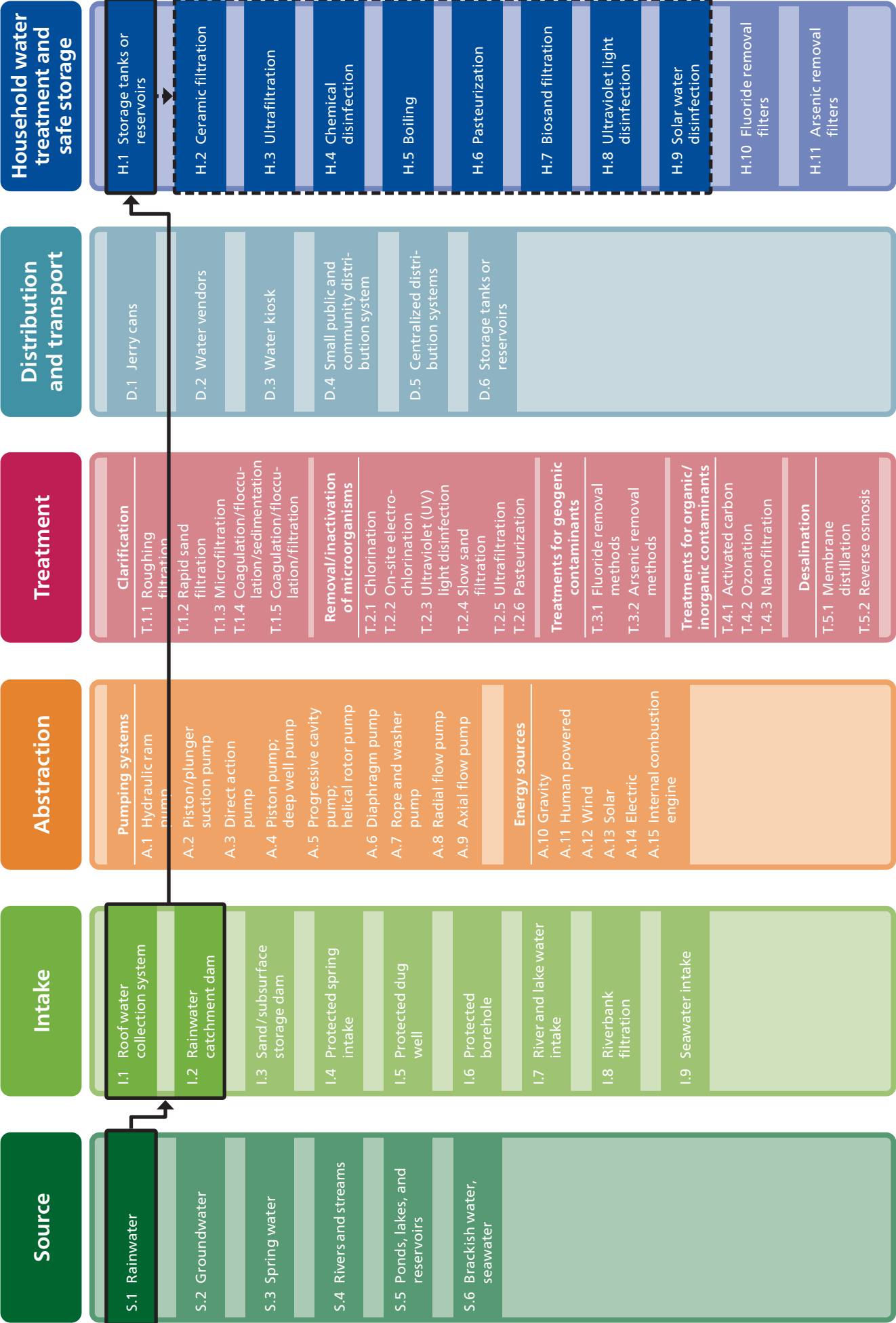
Considerations

This system is only applicable as a major source of water for the time of the year when rain intensity allows sufficient volumes of rainwater to be collected. The material and the size of the roof directly influence the amount of water collected and its quality. Rainwater of a reasonable quality can be collected from roofs out of galvanized corrugated iron, aluminum sheets, stones, tiles, and slates. Metallic paint or similar coatings might impact the taste and colour of the water. Bamboo or straw roofs are least suitable for rainwater collection because they can affect water quality, their permeability leads to water losses, and gutters can be difficult to fix on such roofs. Polyethylene coverings can be used on straw and bamboo roofs to reduce permeability. Where rainwater is collected from asbestos containing roofing, the collected water should be allowed to settle before use, and every effort should be made to avoid degradation and release of fibres from roofing (e.g. avoid cutting and drilling asbestos roofs) (WHO, 2021a). In the absence of a high-quality roof, tarpaulins fixed between poles can be used to collect rainwater.

Although rainwater quality is usually good, roof and storage tank contamination may occur (e.g. from animal activity, vegetation, or aerial deposition from local activities, such as crop spraying or land burning, as well as events such as bushfires). Therefore, roof catchments as well as gutters and tanks should be cleaned regularly to remove dust, leaves, and animal excrement. Although the first-flush mechanism can reduce the contaminants entering the storage tank, where there is a risk of microbial contamination, stored rainwater (see H.1 Storage tanks or reservoirs) should be disinfected prior to consumption either by disinfecting the tank or via household water treatment (see H. Household water treatment and safe storage).

Rainwater harvesting systems are likely to be impacted by the changes in rainfall patterns and intensity associated with climate change. Additional storage capacity might be required to provide adequate water quantity during extended dry periods. Increased rain intensity would require an increase in collection surface area to avoid a reduction in overall rainwater volume captured, which might be difficult. Overall, this might reduce the long-term reliability of rainwater harvesting systems.

System 1 Rainwater harvesting



Dashed lines indicate additional options.

System 2 Centralized surface water treatment

Surface water supplies process water taken from streams, rivers, lakes, ponds, and seas (see S.4 Rivers and streams, S.5 Ponds, lakes, and reservoirs and S.6 Brackish water, seawater). System 2 focuses only on water supplied from non-saline sources. Seawater as a source is instead discussed in System 9 Desalination of brackish and salt water.

Centralized surface water supply systems include intake infrastructure installed in the surface water sources, such as protected or unprotected river and lake intakes (see I.7 River and lake water intake), dams and reservoirs (see I.2 Rainwater catchment dam), or bank-filtration well fields (see I.8 Riverbank filtration). Intake is followed by pumping stations (see A. Abstraction), aqueducts, or piped systems that transport large water volumes over large distances to water treatment facilities. Finally, this system ends with an extensive distribution network, including water storage reservoirs or water towers as well as household tap connections or standpipe (also referred to as tapstand) connections in low-income areas. Surface water typically contains organic and inorganic matter as well as pathogenic microorganisms, necessitating extensive treatment before it can be safely consumed.

Surface water withdrawn from a lake, dam, or river requires an intake structure that:

- allows withdrawal of water at all times despite natural fluctuations in flow, level, temperature, or quality; and
- allows withdrawal of the highest quality water by accounting for natural currents and patterns of sediment deposition, spatial and temporal variations in water quality, quantity of floating debris (including cyanobacteria [or “algal”] scums), ice, rolling stones or blocks, and the location of wastewater discharges and other sources of pollution.

Often in centralized water supplies, the intake structures (see I.7 River and lake water intake) can adjust the depth of the water abstraction point (tower intake), which allows both the selective abstraction of higher quality water and the abstraction of water from variable levels (e.g. in the case of lower levels during prolonged dry periods). Submerged parts or submerged intakes (protected or unprotected) are used for smaller supplies and cannot adjust the depth of the water intake. The withdrawal point is often screened with steel bars or grids to prevent large objects from entering the water supply. Intake chlorination or pre-chlorination is sometimes used to protect pipes from clogging with mussels (e.g. zebra mussels) and to prevent the growth of cyanobacteria and macro- and microorganisms in subsequent steps. However,

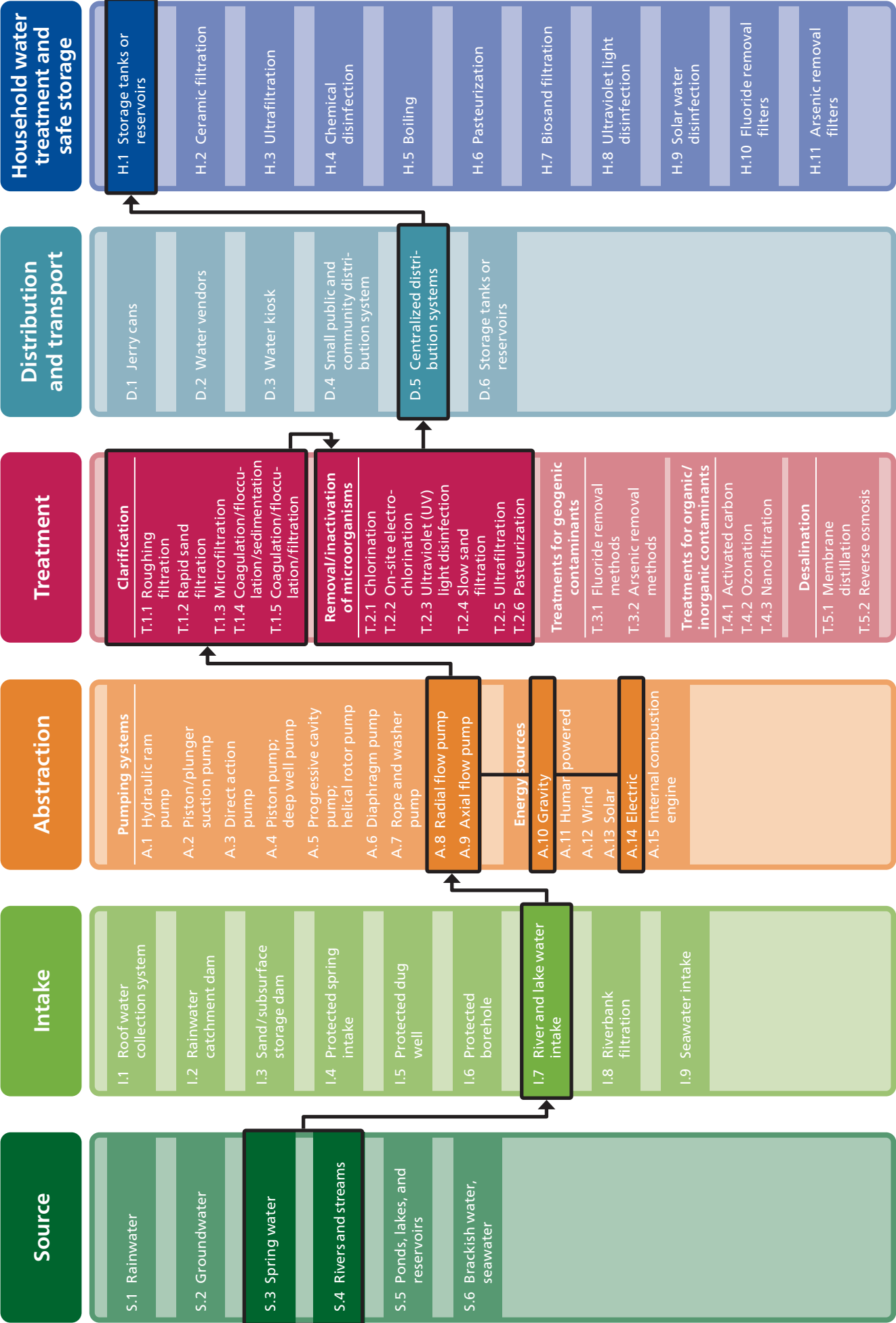
chlorination of untreated water may form undesirable by-products. Riverbank filtration can be a good option, as it serves as an intake structure as well as a pre-filtration process that reduces the contamination and turbidity of water (see I.8 Riverbank filtration).

After conveyance, abstracted water enters a drinking-water treatment plant in which suspended particles and dissolved organics are removed prior to disinfection. Pre-sedimentation followed by coagulation-flocculation and sedimentation and/or filtration are common methods for removing turbidity (see T.1.4 Coagulation/flocculation/sedimentation and T.1.5 Coagulation/flocculation/filtration), and may also remove protozoa, which are typically resistant to chlorine disinfection. During coagulation, chemical coagulants (hydrolyzing iron or aluminum salts) are often dispersed in water by rapid mixing, with pH adjustment when necessary. During flocculation, coagulated particles are aggregated into larger flocs, which are gently stirred by paddles or impellers before transfer to a sedimentation basin, dissolved air flotation system or, for low levels of suspended solids, directly into a sand filter.

After filtration (see T.1.1 Roughing filtration, T.1.2 Rapid sand filtration, T.1.3 Microfiltration), disinfection (see T.2 Removal/inactivation of microorganisms) is performed either by chlorination using chlorine gas, sodium hypochlorite, or chlorine dioxide (see T.2.1 Chlorination), or by ultraviolet (UV) light (see T.2.3 Ultraviolet (UV) light disinfection) or ozone (see T.4.2 Ozonation). The drinking-water can also be treated by adsorption on activated carbon (see T.4.1 Activated carbon), filtration through biologically activated carbon, or slow sand filtration (see T.2.4 Slow sand filtration). Membrane filtration with ultrafiltration membranes (see T.2.5 Ultrafiltration) with or without in-line coagulation is becoming more common for the removal of turbidity and microbial contamination in high-income countries. In low-income countries, capital costs for these membranes are often still higher than for conventional treatment processes and local experience is limited, though this is changing rapidly as well. Post-chlorination (see T.2.1 Chlorination) is often used in the distribution network to provide some protection against low-level microbial recontamination and growth.

Treated water is stored in a protected reservoir or directly distributed through transmission mains to reservoirs, pumping stations, and consumers (see D.5 Centralized distribution systems). The purpose of the distribution network is to supply water at an adequate pressure and flow, avoid its contamination in the distribution network, and ensure that adequate quantities of safe drinking-water reach all parts of the

System 2 Centralized surface water treatment



distribution system. When gravity is insufficient to supply water at adequate pressure, high lift pumps can be used permanently or only intermittently. Water is typically pressurized by pumping it to storage reservoirs constructed at the highest local point in the network. Often a back-up system with a standby pump is used. In many countries, the design capacity of any centralized surface water supply systems depends not only on domestic water needs, but also the supply for firefighting. Thus, the required capacity for firefighting can be the main design criteria for dimensioning intakes, supply, and distribution systems in terms of pipe diameter and pressure. When post-chlorination of treated water is needed, booster stations can be placed at strategic points within the distribution system to ensure that an adequate free chlorine residual is maintained (i.e. ≥ 0.2 mg/L to the point of delivery to the consumer), which can provide some protection against low-level microbial recontamination and growth, including as a result of user practices. Water from household connections is sometimes stored at home in a water tank to account for periods of intermittent supply. The cleanliness of the storage containers and general awareness of the population regarding hygiene is crucial to achieving water safety at the household level (see H.1 Storage tanks or reservoirs).

Considerations

Centralized surface water treatment is most suitable for densely populated urban and peri-urban areas. In rural areas, centralized surface water treatment is prohibitively expensive such that other options should be considered, e.g. Systems 3, 5, 6, 7. Design, construction, and operation of centralized water supply systems requires a large investment; available engineers, construction companies, and trained operators; an available and reliable supply of consumables; financial resources to cover the operational costs of water pumping; resources for the operation and maintenance of the treatment and distribution network; a risk-based water quality management system (see X.4 Risk assessment and risk management, X.5 Water safety planning, X.6 Sanitary inspection); and transparent pricing, water-metering, and accounting systems.

Rapid population growth in cities places existing centralized water supplies under pressure, and attempts to expand existing systems can fail due to a lack of resources and a deteriorating infrastructure. In many cities around the world, water is intermittent, i.e. available only for a restricted number of hours a day, or even a few days per week. Intermittent supply can deteriorate water quality due to challenges in maintaining an adequate free-chlorine residual as well as

increased risks of backflowing water due to reduced pressure, pressure gradients developing from the soil to the pipe, and the development of areas of negative pressure that allow contaminants to infiltrate the pipes. In addition to water quality issues, leakages in distribution systems might result in significant water losses, which may impact the quantity of water available, increase non-revenue water (thereby reducing cost recovery), increase maintenance costs, and result in consumers using alternative, and potentially less safe, water sources. Furthermore, intermittently operated distribution networks or distribution networks with varying pressure make the metering of water usage a difficult task.

System 3 Decentralized surface water treatment

Surface water supplies process water from streams, rivers, lakes, ponds, reservoirs, and seas (S.4 Rivers and streams, S.5 Ponds, lakes, and reservoirs, S.6 Brackish water, seawater). System 3 focuses only on water supplied from non-saline sources. Sea as a source is instead discussed in System 9 Desalination of brackish and salt water.

A decentralized surface water supply system involves the supply and treatment of the generally contaminated water from lakes, streams, rivers, surface water run-off dams, ponds, or reservoirs. It also includes its distribution to the consumer collection point (such as a community standpipe [see D.4 Small public and community distribution system] or water kiosk [see D.3 Water kiosk]) and transport to and storage at home (see H.1 Storage tanks or reservoirs) or its distribution through a distribution network with household connections (see D.5 Centralized distribution systems). Besides the smaller size and number of served consumers, the major differences of this system to the centralized water supply (System 2 Centralized surface water treatment) are the easier construction of intake structures (see I.7 River and lake water intake), less extensive treatment, and relatively short distribution systems with public standpipes (see D.4 Small public and community distribution system) or water kiosks (see D.3 Water kiosk) as well as legal or illegal household connections (see D.5 Centralized distribution systems) that evolve over time. As in centralized surface water treatment systems, the water requires treatment before it can be consumed as it typically contains organic and inorganic matter and pathogenic microorganisms.

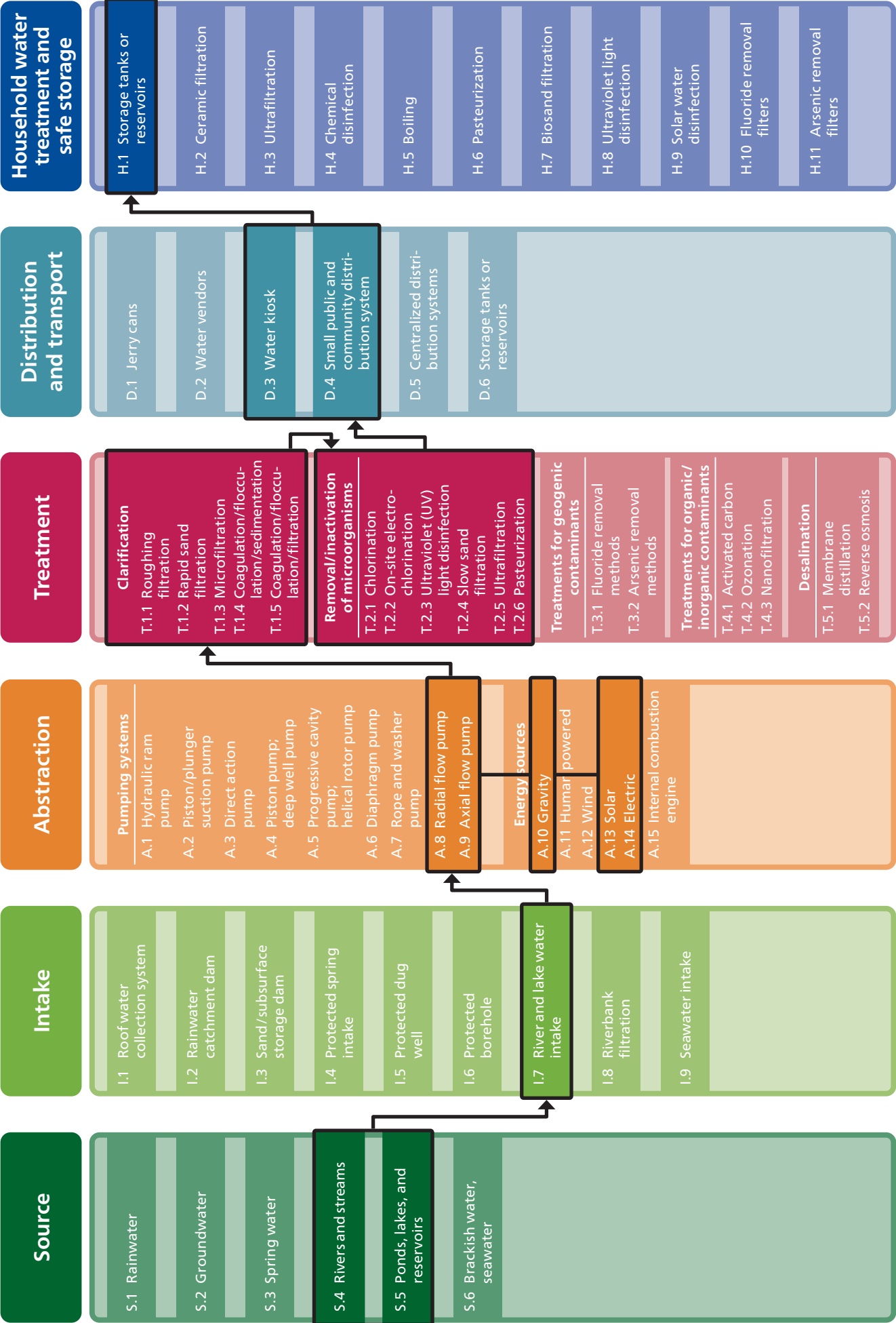
In decentralized community surface water supplies, smaller rivers or streams (see S.4 Rivers and streams) are often used. Thus, adequate waterbody flow and level are needed throughout the year, and the construction of a small submerged weir might be necessary to ensure an adequate water depth year-round. The water should be withdrawn at least 1 m above the ground to avoid sediments entering the water system. Screens are also often placed at the intake site (see I.7 River and lake water intake) to remove floating materials. When boulders or stones are transported by the river, the intake system needs to be protected in stone or concrete to avoid damage. In deep lakes, the water quality throughout the profile of the lake should be considered, and when there is no mixing, it is usually water in the deeper layers that has a lower nutrient content and therefore better quality. River bank filtration can be a good option for both an intake structure as well as a pre-filtration process, reducing the water contamination and turbidity (see I.8 Riverbank filtration).

When water supply by gravity to the treatment facility is not possible, diesel, electric, or solar pumps are placed close to the intake point. As with centralized treatment plants, multi-stage treatment is the preferred option when it is financially and operationally feasible. For turbid water, turbidity removal methods (clarification) are needed (see T.1 Clarification). However, standard methods such as coagulation-flocculation followed by sedimentation and/or filtration (see T.1.4 Coagulation/flocculation/sedimentation and T.1.5 Coagulation/flocculation/filtration) might be difficult to sustainably apply in small systems due to the operational efforts needed to optimize coagulation (as a result of surface water quality variations) and the availability of chemicals required for coagulation. Roughing filtration (see T.1.1 Roughing filtration) followed by rapid or slow sand filtration (see T.1.2 Rapid sand filtration and T.2.4 Slow sand filtration) can be suitable alternatives for small water supplies. Slow sand filtration is often used to remove pathogenic microorganisms but is not a complete barrier.

After clarification, microbial contamination must be addressed (see T.2 Removal/inactivation of microorganisms). In principle, chlorination using chlorine gas, sodium hypochlorite, or chlorine dioxide (see T.2.1 Chlorination); on-site electrochlorination (see T.2.2 On-site electrochlorination); UV light (see T.2.3 Ultraviolet (UV) light disinfection); or ozone (see T.4.2 Ozonation) can be used, though chlorination by sodium hypochlorite is the more common final disinfection step, that can provide some protection against low-level microbial recontamination and growth, including as a result of user practices. Chlorine gas is generally not available nor recommended in small water supplies due to stringent safety requirements. As such, bleach or calcium hypochlorite powder are used for disinfection. Electrochemical on-site generation of hypochlorite solutions is gaining importance for both small- and large-scale water treatment. UV lamps are sometimes used for treatment in water kiosks (see D.3 Water kiosk) or community water treatment systems. Membrane-based systems (see T.1.3 Microfiltration and T.2.5 Ultrafiltration) are becoming a feasible alternative to conventional treatment methods, because turbidity and pathogen removal occurs in one treatment step, space requirements are lower, and operation can be fully automated if required. In high-income countries, many small water supplies have changed from conventional treatment to membrane filtration. In low-income countries, capital costs of membrane-based systems are often still higher than for conventional treatment processes and local experience is limited, but this is also changing rapidly.

When a distribution system is in place (see D.4 Small public and community distribution system), water is

System 3 Decentralized surface water treatment



usually pumped to an elevated storage reservoir from which it is distributed by gravity to consumers or it is pumped directly to the water supply network (although the latter does not provide any supply buffer during pump breakdown or power outages). Sometimes systems are set up such that water by-passes the storage tank, which is used only to store excess water. Generally, branched or looped distribution systems (see D.4 Small public and community distribution system) are used for small-scale distribution. In branched networks, predominantly supplying community standpipes, water is distributed through one main pipe that splits into branches with dead-end connections. Looped networks are used for systems with many household connections, and these systems usually have one or several main loops from which water is conveyed to the consumers via secondary branches or loops. While the looped system is more reliable and less susceptible to contamination, water stagnation, and pressure variations, the design and engineering are more complex, and it has higher capital and operational costs. When using standpipes, water is collected and delivered by households using jerry cans or tanks (see D.1 Jerry cans) and is often stored at home to bridge over periods of intermittent supply. The cleanliness of the storage containers (see H.1 Storage tanks or reservoirs) and general awareness of the population regarding hygiene is crucial to achieving water safety at a household level.

Considerations

Small surface water supplies used to be only recommended for small communities in rural and peri-urban areas where no suitable groundwater source was available. However, with the development and optimization of water-treatment technologies, global deterioration of groundwater quality, and overuse of groundwater, surface water is gaining importance for small decentralized community supplies. In combination with riverbank filtration (see I.8 Riverbank filtration), the need for extensive surface water treatment can also be reduced. The capital and operational costs of decentralized surface water supply systems need to be carefully considered when planning and designing small water supplies and treatment infrastructure. This includes accounting for the availability of resources, such as trained personnel for operating and maintaining the water supply and treatment facility, suitable and reliable energy sources, consumables (e.g. chemical additives and materials/reagents for water quality monitoring), as well as risk management measures (see X.4 Risk assessment and risk management).

When community standpipe connections are used and adequate water treatment and residual chlorination

is not applied or not implemented properly, the awareness of the population regarding safe water transport, storage, and household-level treatment (see H. Household water treatment and safe storage) should be raised.

Intermittent water supply can lead to a decrease in network pressure or even create areas of negative pressure, which increase the risk of water contamination in the distribution system. In addition to water quality issues, leakages in distribution systems might result in significant water losses, which may impact the quantity of water available, increase non-revenue water (thereby reducing cost recovery), increase maintenance costs, and result in consumers using alternative, and potentially less safe, water sources. Furthermore, intermittently operated distribution networks or distribution networks with varying pressure make the metering of water usage a difficult task.

System 4 Freshwater sources: manual transport combined with household water treatment and safe storage

System 4 relies on all freshwater sources (see S.1 Rainwater, S.2 Groundwater, S.3 Spring water, S.4 Rivers and streams, S.5 Ponds, lakes, and reservoirs) used by communities and households and subsequent household water storage and treatment (see H. Household water treatment and safe storage). Brackish or saline water sources (see S.6 Brackish water, seawater) and sources affected by poorly treated industrial and municipal wastewater or agricultural products, such as manure, fertilizers, or pesticides, usually cannot be treated effectively at the household level and should not be considered for this system.

In this system, water is collected manually from nearby water sources, which should be protected whenever possible to minimize the risk of source contamination. Water is carried by family members to the households using jerry cans (see D.1 Jerry cans) or is transported by small water vendors (see D.2 Water vendors (carts and trucks)) using carts, donkeys, bicycles, or tracks. Water is either directly stored in the collection containers or it is stored in water storage tanks (see H.1 Storage tanks or reservoirs) from which it is collected for use.

Water collected from rivers or lakes (see S.4 Rivers and streams and S.5 Ponds, lakes, and reservoirs) without any natural treatment, such as bank filtration (see I.8 Riverbank filtration), is commonly turbid and contains microorganisms, organic matter, and minerals that require treatment (see T. Treatment) as described in Systems 2, 3, and 7. If no centralized or semi-centralized treatments are in place, household water treatment methods are required to remove turbidity before or together with the microbial contamination. Such technologies include, membrane filtration (see H.3 Ultrafiltration), biosand filtration (see H.7 Biosand filtration), and ceramic filtration (see H.2 Ceramic filtration). However, if the turbidity is high, all filtration based technologies are subjected to clogging, requiring frequent maintenance or filter element replacements.

When water is collected from a low turbidity water source (see S.1 Rainwater, S.2 Groundwater, S.3 Spring water), microbial contamination most commonly arises due to a lack of source protection measures or during transport (e.g. via insanitary transport containers, see D.1 Jerry cans). With inadequate source protection, the feasibility of protecting water sources by upgrading or rehabilitating intake structures (see I.1 Roof water collection system, I.4 Protected spring intake, I.5 Protected dug well, I.6 Protected borehole) and other protection measures should be assessed. The principles of water safety planning (see X.5 Water safety planning) can be used to support the safe management of water sources.

If implementing protection measures is not feasible, or if contamination occurs during transport, household water treatment should be used. For low-turbidity water sources, disinfection methods may be applied that include chlorination (see H.4 Chemical disinfection), solar water disinfection (see H.9 Solar water disinfection), ultrafiltration (see H.3 Ultrafiltration), biosand filtration (see H.7 Biosand filtration), or UV (see H.8 Ultraviolet (UV) light disinfection). If transport equipment is used for water collection, dedicated equipment with frequent cleaning and disinfection is crucial for maintaining good water quality (see D.1 Jerry cans and D.2 Water vendors (carts and trucks)). Treated water should always be stored in safe water storage devices (see H.1 Storage tanks or reservoirs).

Water contaminated with geogenic contaminants (arsenic, fluoride) can also be treated at the household level (see H.10 Fluoride removal filters and H.11 Arsenic removal filters). However, many arsenic removal methods are less reliable or more complex at the household level compared to community-level water treatment (see T.3.2 Arsenic removal methods). Methods addressing microbial contamination might be needed afterwards (e.g. combined filters including fluoride filtration media with ceramic candle filter).

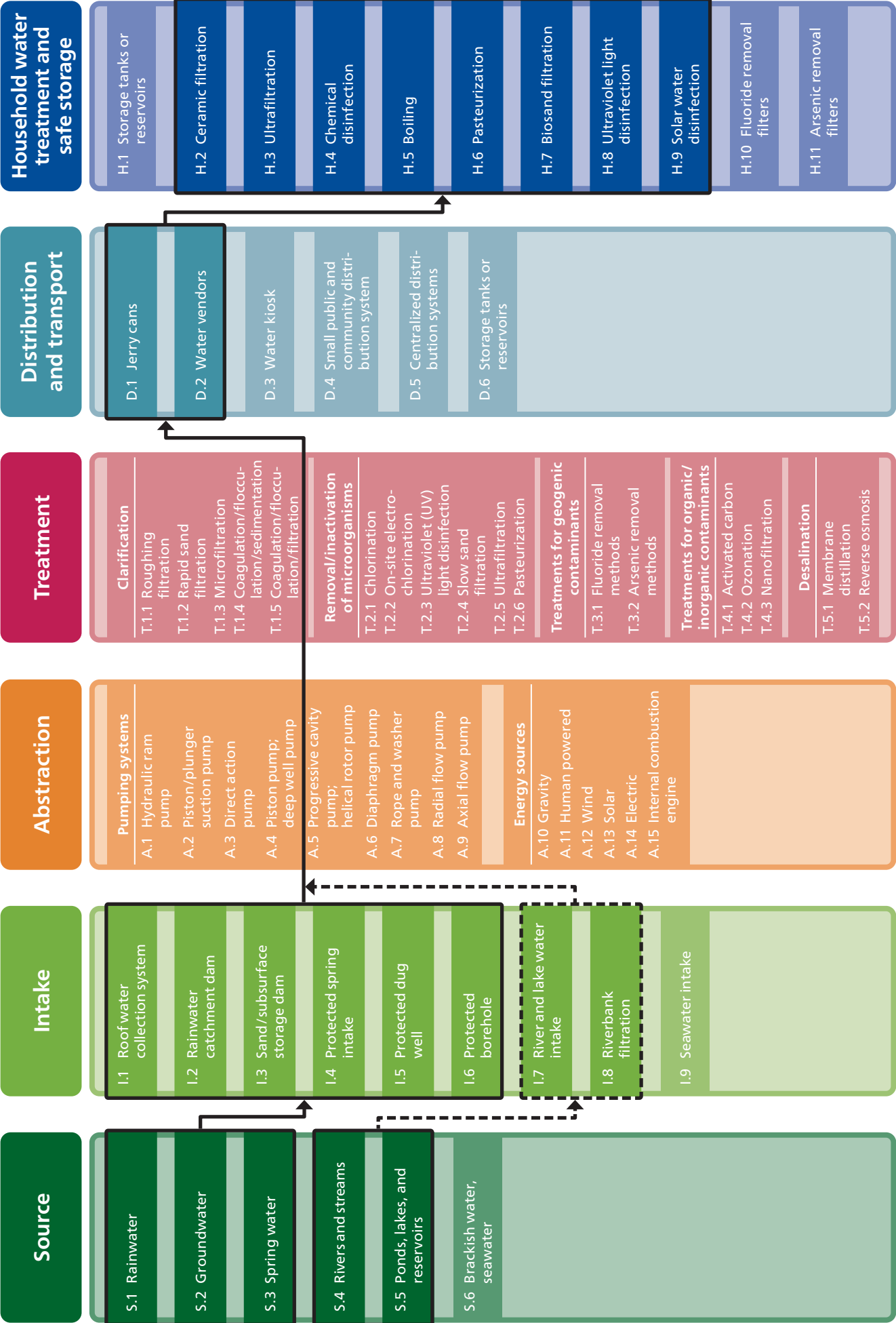
Considerations

This system is common in rural and peri-urban areas where freshwater sources are available, accessible, and widely used for different purposes (e.g. bathing, irrigation, etc.) by the population. In these contexts, large investments to improve the water supply are rarely foreseen in the near future.

Considering freshwater sources are likely to be contaminated, a number of factors need to be addressed to minimize adverse health effects. This includes the availability and financial and physical accessibility of household water treatment technologies, the awareness of the population regarding their safe use, and the possibility of awareness raising and behaviour change campaigns as well as trainings on safe household water storage and hygiene.

Attention and support must be given to monitoring and quality assurance of household water treatment systems since households are responsible for their own water supply and often do not possess the required knowledge or resources to sustainably operate, maintain, and monitor their systems.

System 4 Freshwater sources: manual transport combined with household water treatment and safe storage



Dashed lines indicate additional options.

System 5 Gravity flow supplies

Gravity water supply systems can be considered for water sources that are located at a higher elevation than the settlement they are serving. These systems use the driving gravitational force of elevated sources to transport water by pipelines to storage tanks, treatment facilities, or directly to the supply points (see A.10 Gravity). These systems usually rely on protected springs (see S.3 Spring water) as a water source, but surface water sources (see S.4 Rivers and streams and S.5 Ponds, lakes, and reservoirs) can also be used as long as there is treatment before distribution (see T. Treatment) and/or at the household level as required (see H. Household water treatment and safe storage). There are also mixed systems that use pumping at the source and can apply gravity at certain points within the system. For example, a mixed system can pump water from a protected borehole (see I.6 Protected borehole) to a storage tank (see D.6 Storage tanks or reservoirs) from where it is transported and distributed through gravity.

The typical community gravity flow water supply system includes a protected spring intake (see I.4 Protected spring intake) situated at a certain elevation and connected to a header reservoir (header tank). The header reservoir is usually situated below the spring catchment. The part of the system connecting the protected spring intake with the header reservoir should ideally be unpressurized. This can be achieved by choosing a larger pipe diameter and a sufficient height difference between the reservoir and the spring.

From the header reservoir, water is delivered through pipes to a downhill reservoir (storage reservoir). The height difference between the two reservoirs determines the pressure (static pressure) that the water pipes must resist. Break pressure tanks can be installed to reduce the pressure on the pipes and protect them from breakage. However, pressure can also be lost in the pipes due to the flow, roughness of the pipe material, pipe diameter, length, and form irregularities. These factors need to be considered when designing a gravity flow supply to guarantee that sufficient pressure exists for water to reach the consumer (e.g. household tap, standpipe).

In general, the storage reservoir should be located as close as possible to the community to be accessible for maintenance, to reduce the distribution network length, and to possibly allow overflow water to be used for other needs (e.g. livestock watering, irrigation). From the storage reservoir, water is distributed to community standpipes or feeds into the community

distribution network (see D.4 Small public and community distribution system).

Protected springs (see I.4 Protected spring intake), if carefully designed and maintained and with adequate protection of the catchment area, have a reduced risk of contamination at the source. However, reliable protection of the spring catchment can be difficult. Spring water quality can also vary due to precipitation patterns. To protect or enhance spring water quality during distribution/storage, reservoir disinfection should be applied (e.g. through chlorination [see T.2.1 Chlorination]). Household water treatment methods (see H. Household water treatment and safe storage) can also be used when there is a risk of contamination in the distribution network or during transport from the standpipes or storage reservoir to the households.

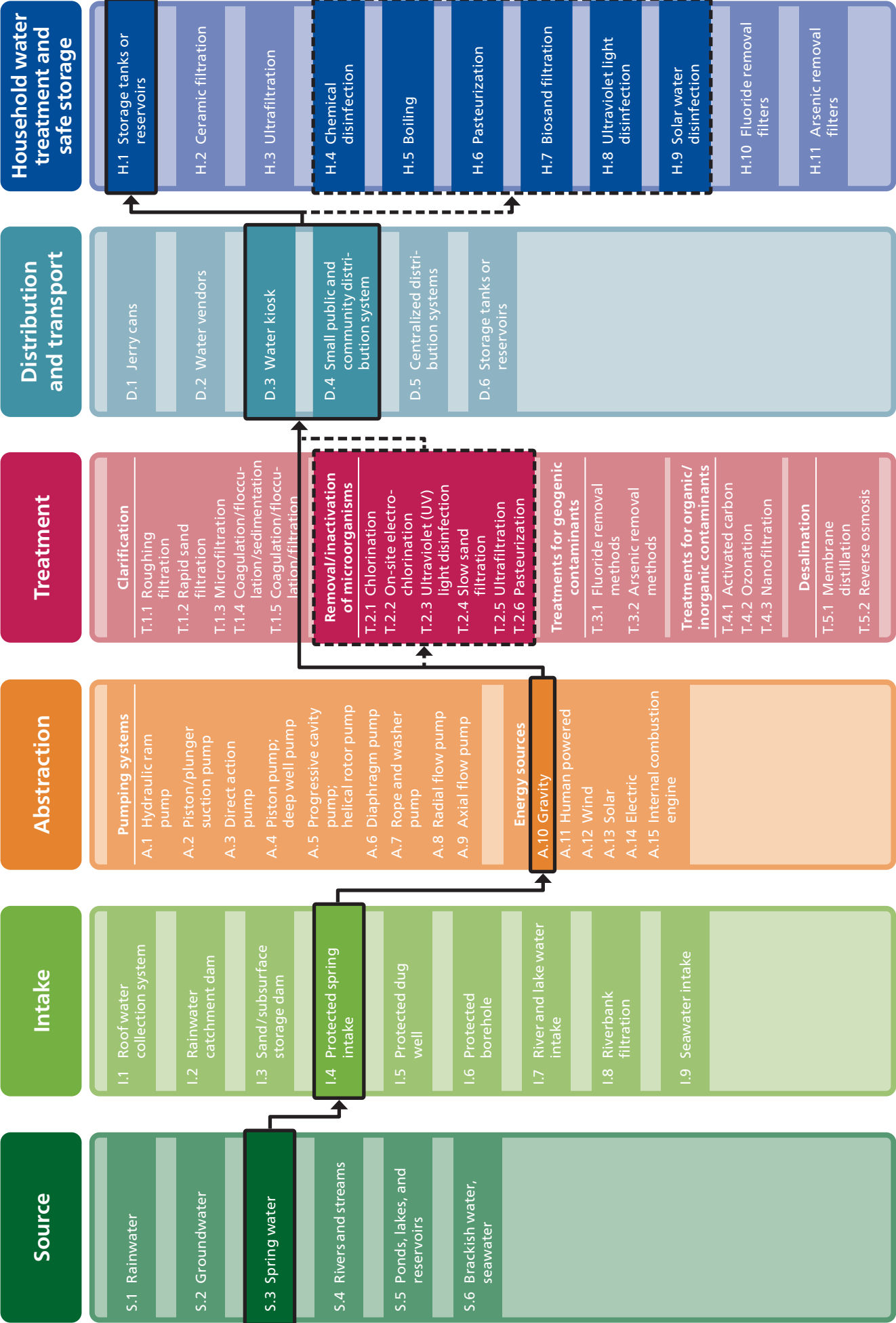
Considerations

Gravity flow water supply systems only work properly when supply pipes are full of water and air locks are avoided. This requires proper pipe sizing, careful topography considerations, and installation or air release valves (see A.10 Gravity).

Gravity flow systems are usually one of the cheapest and easiest options, as no external energy is required to maintain water flow. However, at the community scale, proper management of the water supply system, including protection of water source catchment, maintenance of pipes and reservoirs, and disinfection at the storage reservoir, is required to ensure long-term sustainability and water safety (see X.4 Risk assessment and risk management and X.5 Water safety planning).

When water is not disinfected or disinfection is not properly implemented, the awareness of the population regarding the issues of safe water transport, storage, and household-level treatment (see H. Household water treatment and safe storage) should be raised.

System 5 Gravity flow supplies



Dashed lines indicate additional options.

System 6 High-quality groundwater

Systems based on the use of high-quality groundwater (see S.2 Groundwater and S.3 Spring water) ensure that it is free from harmful contaminants and is protected from contamination at all levels – from intake, through transport and storage, to use at households. All unprotected groundwater source intakes (see details on unprotected intakes in I.4 Protected spring intake, I.5 Protected dug well and I.6 Protected borehole) are generally subjected to contamination and should not be used in this system.

Groundwater quality depends strongly on a number of local factors, including the geological conditions, soil type, location in relation to sources of contamination, adequacy of type of extraction technology, depth of the aquifer, and the presence of existing source-protection measures and their efficacy. Deep dug wells (see I.5 Protected dug well) or boreholes (see I.6 Protected borehole) need to be protected to prevent the risk of deteriorating water quality. Protected spring intakes (see I.4 Protected spring intake) that eliminate surface water intrusion and protect the catchment area can also provide water with a reduced risk of contamination. However, the water quality can vary greatly depending on precipitation and protection measures in place.

In these systems, high-quality groundwater (see S.2 Groundwater and S.3 Spring water) is collected through a protected intake system, which could be a spring intake (see I.4 Protected spring intake), dug well (see I.5 Protected dug well), or borehole (see I.6 Protected borehole). Water is abstracted from protected dug wells or boreholes by motorized or manual pumping (see A.2 Piston/plunger suction pump, A.3 Direct action pump, A.4 Piston pump; deep well pump) depending on the depth of the well, available energy sources, and available human and financial resources. Water from protected dug wells (see I.5 Protected dug well) can be manually pumped by consumers or water vendors (see D.2 Water vendors (carts and trucks)) and collected into clean transport containers (see D.1 Jerry cans). Water can also be pumped to a distribution system (see D.4 Small public and community distribution system) that delivers it to consumers, a public standpipe, or a water enterprise (e.g. water kiosk [see D.3 Water kiosk] or bottling facility), with excess water flowing to a storage tank (see D.6 Storage tanks or reservoirs). Alternatively, water can first be pumped to an elevated storage tank from which it is distributed by gravity to consumers (see A.10 Gravity and D.4 Small public and community distribution system). If topography permits, gravity-based systems (System 5 Gravity flow supplies) can be built to distribute water without

pumping. High-quality groundwater can also be bottled or filled into clean jerry cans (see D.1 Jerry cans), transported by water trucks (see D.2 Water vendors (carts and trucks)), or sold through water kiosks (see D.3 Water kiosk) – assuming that good water quality is maintained by the user, service provider, or business owner.

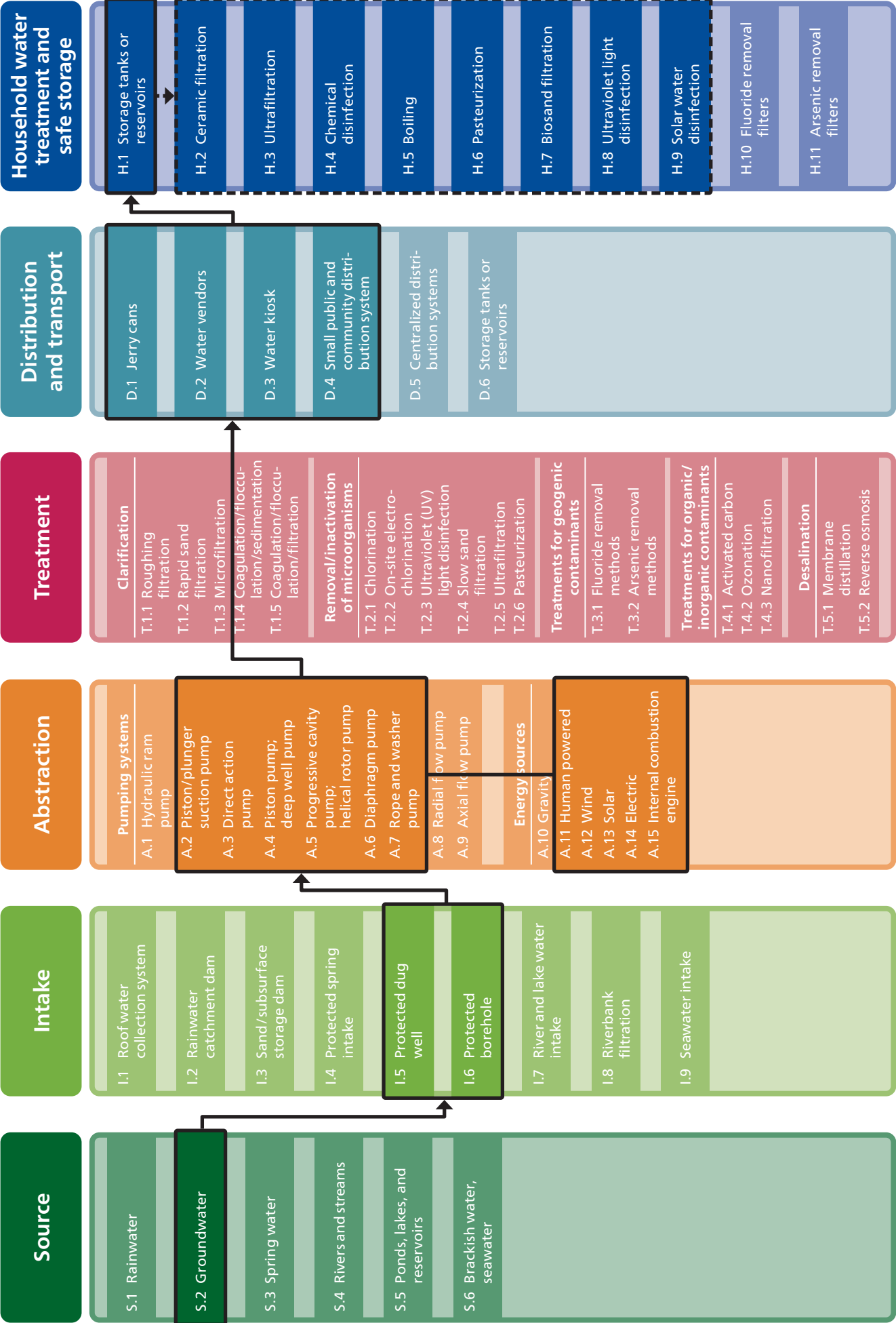
In areas with unreliable energy supply, safe water storage tanks (see H.1 Storage tanks or reservoirs) at households (e.g. rooftop, ground level, or underground) can be used to cover for interruptions in the water supply.

Considerations

This system can be used anywhere high-quality groundwater is available, source protection measures are possible, or the hydrogeological situation allows for the construction of new protected dug wells or boreholes. Siting for a dug well or borehole usually requires a hydrogeologist with considerable practical expertise and information on the local geological conditions. The capital investment required for this system is considerable when dug wells and boreholes need to be built to access a groundwater source. As such, the rehabilitation of existing dug wells or boreholes should be done where possible. Maintenance of the intake structures, pumps, and distribution network requires the availability of trained personal and financial resources, possibly collected through water tariffs.

When a high-quality water aquifer is tapped and its intake structures are properly designed, constructed, and protected, the raw water should be free from high concentrations of suspended organic and inorganic particles and pathogenic organisms. However, if water is abstracted from aquifers with high organic matter content, sub- or anoxic conditions may occur. Water with depleted oxygen can contain iron and manganese, which need to be removed via aeration followed by the sedimentation and/or filtration of formed precipitates. In any case, if there is a risk for microbial contamination in the distribution network or during storage, disinfection (e.g. with chlorine, see T.2.1 Chlorination) is required. If this is not done or not implemented properly, the awareness of the population regarding the issues of safe water transport, storage, and household level treatment (H. Household water treatment and safe storage) should be raised. If transport equipment is used for water collection, dedicated equipment with frequent cleaning and disinfection is crucial to maintain good water quality (see D.1 Jerry cans, D. 2 Water vendors). Household water treatment methods can also be applied as described in System 4 Freshwater sources.

System 6 High-quality groundwater



Dashed lines indicate additional options.

System 7 Groundwater subjected to geogenic contamination

This groundwater-based (see S.2 Groundwater) system is similar to System 6 High-quality groundwater, though in System 7 Groundwater subjected to geogenic contamination, abstracted groundwater contains geogenic (naturally occurring) contaminants and therefore requires treatment prior to consumption.

Geogenic contamination stems from interactions between the rocks in aquifers and the groundwater, which may release substances that can be harmful when consumed over long periods. Of all naturally present contaminants in drinking-water, arsenic (As) and fluoride (F) represent the greatest threats to human health and affect millions of people worldwide. Elevated manganese (Mn) is an issue that also affects many parts of the world, including groundwater supplies. WHO has therefore derived guideline values for these chemicals. Guideline values typically represent a concentration of a chemical without a significant health risk over a lifetime of consumption and are intended to support countries in setting their own drinking-water quality regulations and standards. The WHO guideline values for drinking-water are 0.01 mg/L for As,¹ 1.5 mg/L for F and 0.08 mg/L for Mn (WHO, 2022a).² Other contaminants such as selenium, uranium, boron, and chromium can be a problem as well, but their presence is usually localized and limited in extent. Iron may affect the taste, odour, and appearance of water and therefore consumer acceptability, but is not a direct threat to human health at the concentrations typically found in groundwater. However, water that is unacceptable to consumers may indirectly pose a health risk if it results in reduced consumption leading to dehydration or in consumers seeking alternative, less safe, water sources.

The treatment of geogenic contamination is more complex and often more costly than the treatment of microbially contaminated water. Therefore, the use of alternative microbiologically safe water sources (treated surface water, rainwater, groundwater from different aquifers) or the potential for dilution with non-contaminated sources should always be considered before water-treatment systems are built. When suitable alternatives are not feasible or available, contaminated sources (e.g. groundwater wells) should be upgraded with a treatment step. Many technologies exist for removing As and F contamination at different scales (see T.3.1 Fluoride removal methods, T.3.2 Arsenic removal methods, H.10 Fluoride removal filters, H.11 Arsenic removal filters).

Household water filters that remove arsenic or fluoride may be used (see H.10 Fluoride removal filters, H.11 Arsenic removal filters), but treating water at the

source on a community scale (see T.3.1 Fluoride removal methods and T.3.2 Arsenic removal methods) is usually preferable, as the treatment efficiency can be monitored more easily. When community treatment is needed, water is usually pumped mechanically and delivered to the community water-treatment point. Treatment systems may also be installed directly at a community hand pump. The technologies for treating arsenic at a community scale (see T.3.1 Fluoride removal methods, T.3.2 Arsenic removal methods) often include a pre-treatment step to oxidize As (III) to As (V). As (V) can then be removed by coagulation/precipitation using aluminum and iron salts, precipitation with naturally occurring iron, membrane methods, adsorption on granular activated alumina or iron-based solids/metallic iron, or ion exchange using various strong-base anion exchange resins. Fluoride removal technologies are based on fluoride adsorption on filter beds using calcium phosphate- or aluminum-based solids, precipitation/coagulation techniques, or membrane-based techniques such as reverse osmosis.

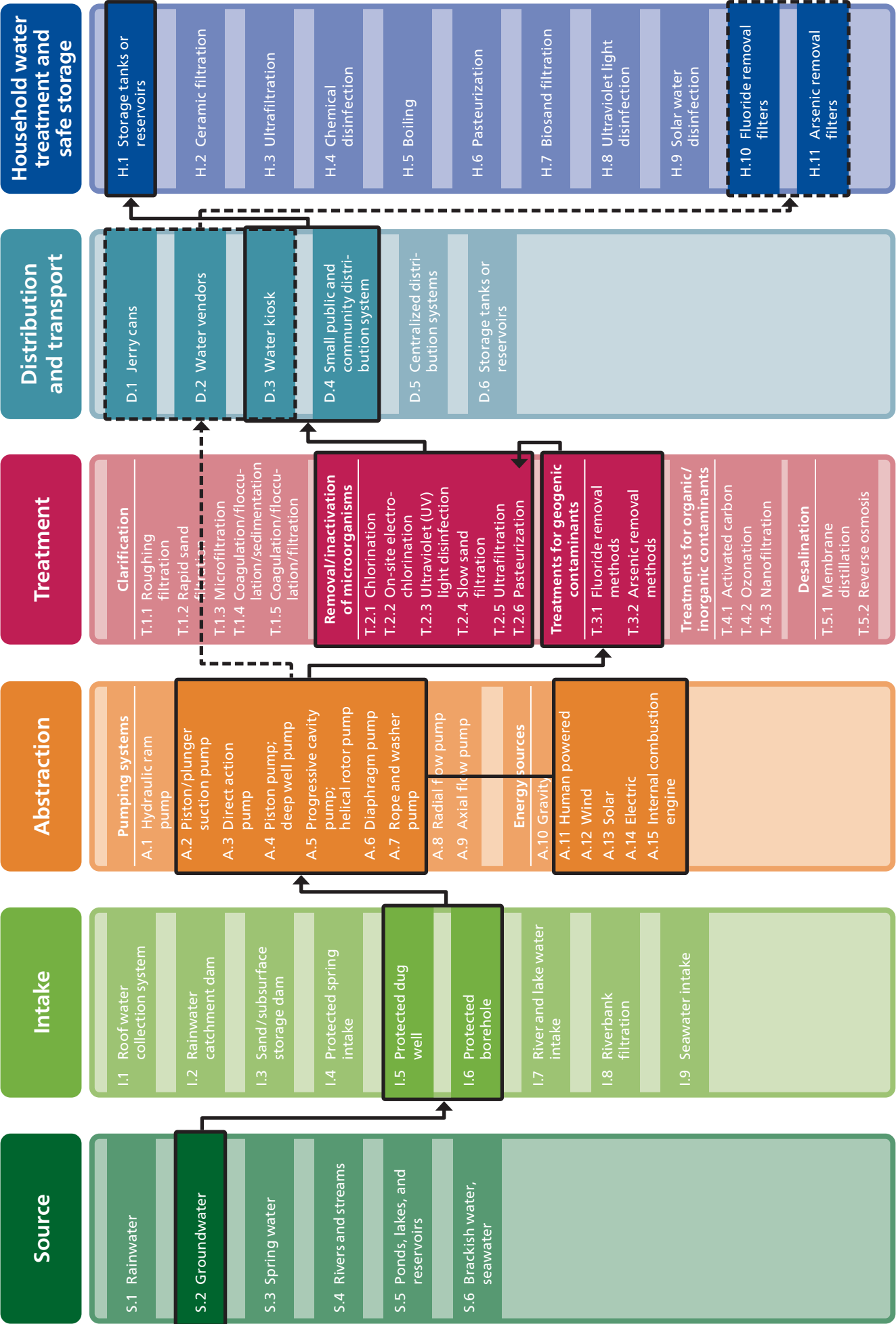
Since treating geogenic contamination requires considerable investments and the raw water might be safe for washing and cleaning, treated water for drinking and cooking purposes can be sold in water kiosks (see D.3 Water kiosk). When decentralized or semi-centralized treatment is involved, distribution networks similar to those used for System 2 Centralized surface water treatment, System 3 Decentralized surface water treatment, or System 5 Gravity flow supplies are used.

Considerations

All filtration processes used in As and F removal are based on physical or chemical adsorption, meaning that the filters will reach their adsorption capacity at a certain point and will need to be replaced. If water quality monitoring is not performed regularly to detect required filter replacements, the concentrations of the contaminants in the drinking-water will increase and be undetected by operators or users. Estimations of the uptake capacity of filtration material based on water use and raw water concentrations, together with simple semi-quantitative water quality tests can help to establish a timely maintenance schedule (e.g. see X.9 Water quality monitoring).

- 1 The guideline value for As is provisional, and is based on the difficulties with removing arsenic to lower levels using conventional water treatment. Every effort should therefore be made to keep concentrations as low as reasonably possible and below the guideline value when resources are available.
- 2 The guideline value for Mn is provisional due to uncertainties in the health-effects database. Incremental improvement towards meeting the provisional guideline value is encouraged, in situations where it is unfeasible to achieve.

System 7 Groundwater subjected to geogenic contamination



Dashed lines indicate additional options.

System 7

Water sold or distributed as safe from geogenic contamination might still contain pathogenic microorganisms, so water from shallow wells still needs to be assessed for microbial contamination. In any case, if there is a risk for microbial contamination in the distribution network or during storage, disinfection is required (e.g. with chlorine, see T.2.1 Chlorination). If transport equipment is used for water collection, dedicated equipment with frequent cleaning and disinfection is crucial to maintain good water quality (see D.1 Jerry cans, D.2 Water vendors (carts and trucks)).

System 8 Freshwater sources subjected to anthropogenic contamination

This system is based on freshwater sources (see S.2 Groundwater, S.3 Spring water, S.4 Rivers and streams and S.5 Ponds, lakes, and reservoirs) with anthropogenic contamination that are the major source of water supply when naturally safe sources are unavailable or not perennially accessible.

Anthropogenic contamination, i.e. pollution through human activity, can significantly impair the quality of water sources. Particularly in densely populated areas, elevated concentrations of chemical contaminants arising from industrial activities, human dwelling, and agricultural activities can be present in drinking-water sources. They can include but are not limited to pesticides, fertilizers, industrial chemicals, and hydrocarbons, as well as cyanobacterial toxins that arise from blooms caused by human activity. These contaminants can be released from point sources, such as dysfunctional or overloaded sewage treatment plants and industrial production sites, as well as from diffuse sources like surface run-off from agricultural land and roads. An extensive overview of potential chemical and microbial hazards in surface water and groundwater and how to mitigate them is given in the WHO publications (2006) *Protecting groundwater for health* and (2016a) *Protecting surface water for health*.

This system is generally similar to Systems 2 and 3. Surface or groundwater is abstracted through protected or unprotected river or lake intakes (see I.7 River and lake water intake), dams or reservoirs (see I.2 Rainwater catchment dam, I.3 Sand/subsurface storage dam), or protected springs, dug wells, or boreholes (see I.4 Protected spring intake, I.5 Protected dug well, I.6 Protected borehole). Intake systems containing some form of natural treatment, such as river or lake bank filtration (see I.8 Riverbank filtration), can make use of the treatment capacity of the soil and the soil groundwater system. This can significantly reduce the particulate and microbial load and further reduce the organics prior to the specific technical unit process, which will increase its effectiveness. Abstracted water is pumped or supplied by gravity to the treatment plant. Anthropogenic contaminants are usually addressed after reductions in the turbidity (see T.1 Clarification) and microbial contaminants (see T.2 Removal/inactivation of microorganisms) by advanced water treatment methods. These technologies generally address particular contaminant classes. Therefore, constructing an appropriate drinking-water treatment system requires information to be available on the concentration and physicochemical properties of the contaminants present in the source water. Depending on the type of anthropogenic contaminant, the treatment methods can include ozonation (see T.4.2 Ozonation) to reduce organic contaminants by destruction, adsorption

by granular activated carbon (GAC) (see T.4.1 Activated carbon), removal by nanofiltration (NF) (see T.4.3 Nanofiltration), removal by reverse osmosis (RO) (see T.5.2 Reverse osmosis), and in special cases, ion-exchange resins. Depending on the technology used, post-disinfection might be applied after treatment and distribution through community or large-scale distribution systems.

Micropollutants, such as pharmaceutical compounds and their metabolites, can be present in very low levels ($< 0.1 \mu\text{g/L}$). The risk of these micropollutants to human health, like for all chemicals, is a function of exposure and toxicity. However, given the extremely low concentrations of many pharmaceuticals, the health risks are likely to be low. Practical guidance and recommendations on managing concerns about pharmaceuticals in drinking-water can be found in the WHO publication (2012a) *Pharmaceuticals in drinking-water*.

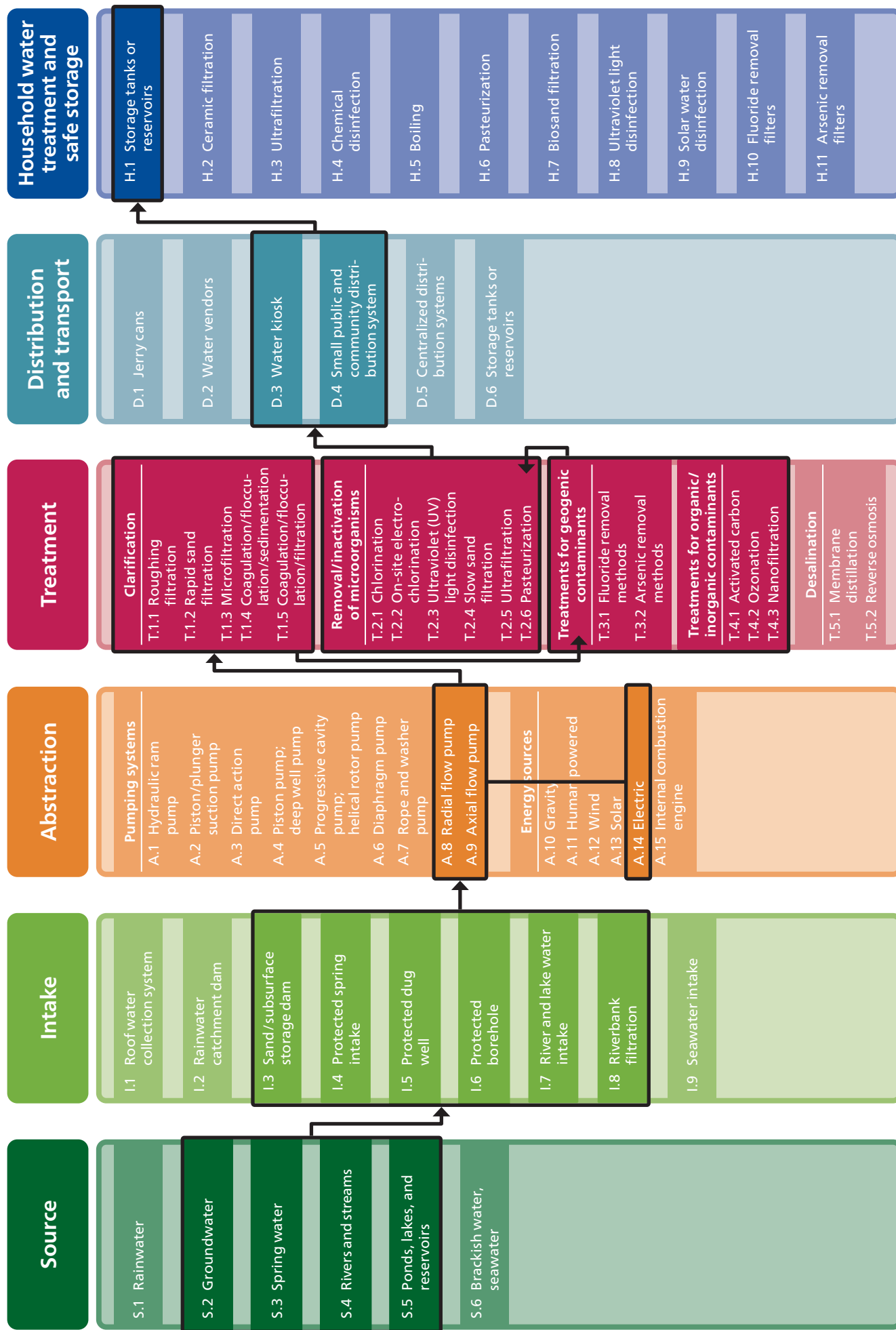
Considerations

The design, construction, and operation of such advanced treatment systems requires a high investment, trained engineers and operators, construction companies, and an available and reliable supply of consumables and financial resources to cover operational and maintenance costs, as well as monitoring costs. Often, a more sustainable and cost-effective approach involves mitigation strategies to reduce the point contamination of source waters. Thus, this system should only be applied if high-quality water sources are unavailable or a reduction in point contamination cannot be achieved.

System selection should always consider types and concentration of contaminants, so a comprehensive assessment of source water quality along with documentation of relevant activities in the local catchment area (both observed and expected) is required. The chemical and microbial contaminants in the freshwater sources can vary significantly in concentration and composition over time. In addition to continuous contamination events, shock loads may arise through events such as an overflow of sewage, spills of waste or chemicals, seasonal use of chemicals (e.g. in agriculture), and rainfall patterns.

In general, organic contaminants are better removed by adsorption onto GAC than by NF, though frequent replacement of the GAC needs to be considered. For NF and RO, an important aspect for process selection is the water recovery rate, which is the percentage of feed water converted to product water (permeate). Lower water recoveries are typical for dense membrane processes, which produce a concentrate containing the retained contaminants in addition to the permeate used for drinking-water supply. The concentrate from RO or NF is mostly discharged as wastewater and requires further treatment.

System 8 Freshwater sources subjected to anthropogenic contamination



System 9 Desalination of brackish and salt water

This system should be used as a major source of water supply only if freshwater sources are not available or accessible. Desalination removes contaminants and salts from brackish or seawater (see S.6 Brackish water, seawater).

Brackish or seawater has an increased content of dissolved salts, mostly sodium chloride, as well as magnesium sulfate, potassium nitrate, or sodium bicarbonate. Seawater typically has a salinity of around 35 g/kg, with lower values near the coast or close to the inflows of rivers. Brackish water is a mixture of fresh and seawater and can be characterized by salinity values of 0.5–30 g/kg. Brackish or seawater can be treated for drinking by reducing the total salinity to less than 1000 mg/L (approximate electric conductivity of 1.6 mS/cm). Chloride concentrations above 250 mg/L can also give a detectable taste to water and may cause consumer acceptability issues, even if there is no health-based guideline value. Excessive chloride concentrations may also increase the corrosion rate of metals in the distribution system, leading to increased concentrations of metals in the supply (e.g. iron, copper).

Brackish water or seawater (see S.6 Brackish water, seawater) is abstracted through different types of intakes, e.g. beach wells or open intakes and their respective abstraction systems, before it is transferred to the water treatment system. Seawater intake systems (see I.9 Seawater intake) comprise some form of filtration, such as beach wells, which make use of the natural treatment capacity of sand. This significantly decreases the particulate and microbial load and reduces the pretreatment requirement.

The treatment is done at desalination treatment plants. Pretreatment such as membrane filtration or multi-media filtration (see T.1 Clarification, T.2.5 Ultra-filtration) are used to remove turbidity prior to the actual desalination stage (see T.5 Desalination). Currently, reverse osmosis (RO) (see T.5.2 Reverse osmosis) is the state-of-the-art technology in desalination, while several other technologies, such as membrane distillation (T.5.1 Membrane distillation) or electrodialysis, are emerging and applicable in certain scenarios. The produced permeate (see T.5.2 Reverse osmosis) or distillate (T.5.1 Membrane distillation) then often undergoes a post-treatment step to adjust the pH and remineralize the water. This is often done with lime or dolomite, to add health- and taste-related bivalent ions like calcium and magnesium to the almost salt-free desalination product water prior to distribution and consumption. Remineralization can also reduce the corrosivity of desalinated water, which is important to protect downstream components.

Considerations

Handling the brine, which is the concentrate of removed salt and minerals, is one particular concern in desalination by thermal or membrane processes. In seawater desalination, the brine is often discharged to the sea. Brackish water desalination requires other solutions for landlocked plant locations. The brine can be discharged as wastewater, stored in evaporation ponds, further treated toward zero-liquid discharge (costly), or used for aquaculture or the irrigation of halophilic ("salt-loving") plants.

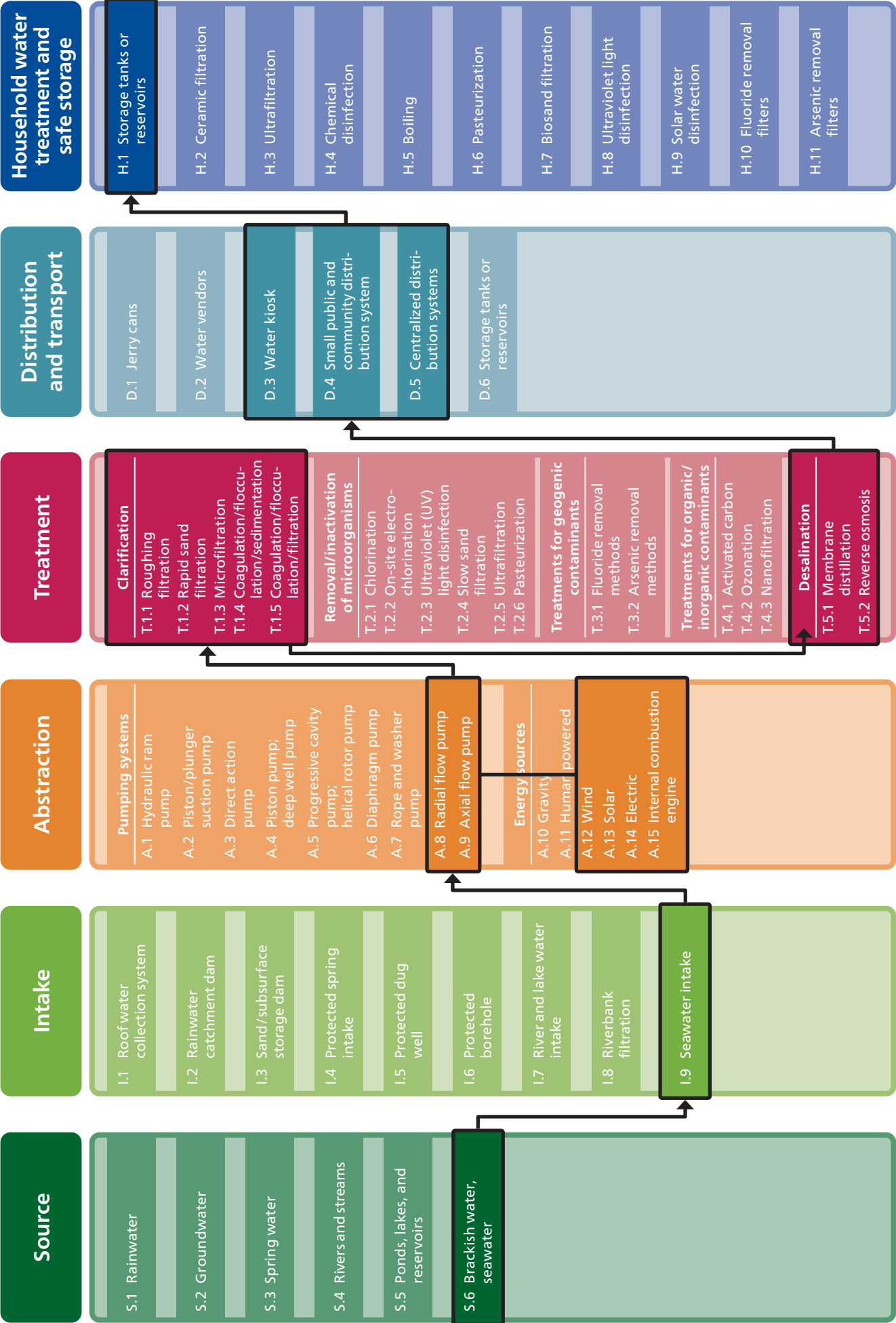
System designs have to consider the site-specific salinity and ion composition of the raw water to be desalinated, particularly to define the achievable recovery rates and optimum energy usage as well as to avoid the formation of salt deposits (scaling) in the desalination plant.

The energy consumption of desalination systems is significantly higher than conventional drinking-water treatment systems. Although the specific energy consumption for desalination in seawater RO plants has significantly declined in recent decades due to technological improvements, it still ranges around 3–4 kWh/m³ compared to 0.1 kWh/m³ for conventional surface water treatment systems as described in System 2 Centralized surface water treatment. Brackish water units require less energy due to the lower salinity.

Desalination coupled with a solar power supply (see A.13 Solar) or wind power (see A.12 Wind) can be reliably operated in remote locations. If energy is generated by a diesel generator (see A.15 Internal combustion engine – diesel and petrol), low grade heat can be used to desalinate the water by thermal processes, such as membrane distillation. However, desalination treatment plants at any scale are highly complex multi-stage treatment systems that require a high level of automation and expertise to ensure reliable operation and maintenance.

For further information on drinking-water quality considerations for salt water, refer to WHO (2011) *Safe drinking-water from desalination*.

System 9 Desalination of brackish and salt water



Part 2 | Technology information sheets

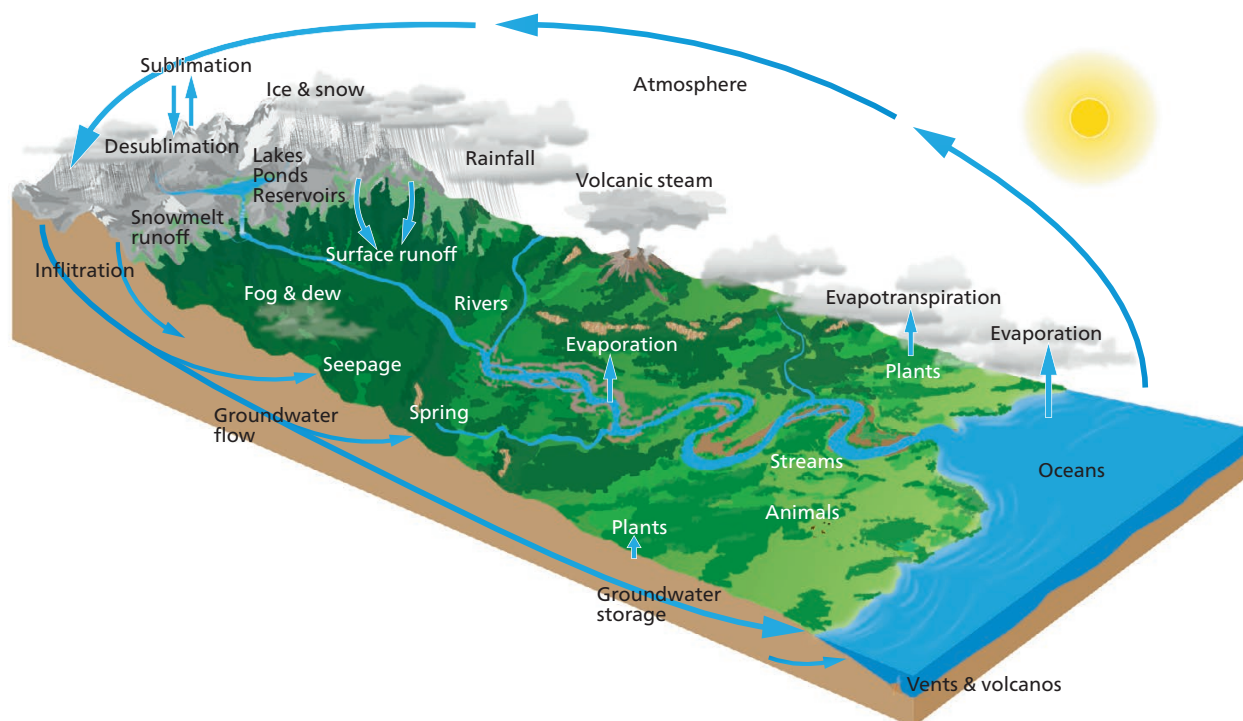
The second part of the Compendium provides an overview of the various water supply technologies within each functional group (Source, Intake, Abstraction, Treatment, Distribution and Storage, Household water treatment and safe storage).

The technologies are presented in Technology Information Sheets. These summarize the (i) main features of technological design, (ii) applicability and adequacy of the technology, (iii) main operational and maintenance requirements, and (iv) any health and environmental implications of applying this technology as well as major acceptance issues. The references and further sources of information are listed at the end of the Compendium.

The table at the top of each technology sheet indicates in which system template the technology can be found and on which management level the technology should be operated and maintained. It describes whether technology elements and components are likely to be locally available and whether the technology is well established or relatively new. Table 1 summarizes different options. In the Source section, only applicability to systems is mentioned.

Table 1
Technology information sheet summary table explained

Applicable to systems 1, 2, 3, 4, 5, 6, 7, 8	Management level Household/school/health center/community/centralized	Local availability of technology or components Yes/no/mostly/occasionally	Technology maturity level Established technology/new technology
Indicates in which system template the technology can be found	Describes which management approach is appropriate for the operation and maintenance of the technology	Indicates whether technology components are locally available	Describes whether a technology is established or relatively new



To establish a water supply system, a resource providing sufficient quantity of water should be available. These systems are commonly based on groundwater or surface water resources, though in areas with sufficient rainfall, rainwater can also be an appropriate water resource. The quantity and quality of the source water determine the required water treatment and water supply system design. Depending on the source, water resources usually contain dissolved or particulate matter and gases as a result of interaction with the atmosphere, minerals in rocks, natural organic matter, and macro- and microorganisms. Anthropogenic activities further impact the quality of these water resources.

This section describes water resources that can be used for drinking-water supply and covers:

S.1 Rainwater

S.2 Groundwater

S.3 Spring water

S.4 Rivers and streams

S.5 Ponds, lakes, and reservoirs

S.6 Brackish water, seawater

Rainwater (S.1 Rainwater) is generally used as a supplementary source of water, which often requires storage tanks.

Groundwater (S.2 Groundwater, S.3 Spring water), the water below the surface of the earth, is generally better protected from microbial contamination. However, that does not mean it is always safe. Depending on the environmental conditions and location, it can be contaminated with pathogenic microorganisms. In some regions, it can also be affected by chemical contamination, such as by fluoride, arsenic, iron, manganese, or high salinity. Localizing groundwater abstraction sites and estimating available groundwater quantities is a complex task that requires drilling and pumping equipment for abstraction (see A. Abstraction).

Surface water sources such as rivers and streams (S.4 Rivers and streams) or ponds, lakes, and dams (S.5 Ponds, lakes, and reservoirs) are easily accessible. Generally, surface water may contain a higher concentration of microbial contamination and may be turbid (cloudy). Thus, it requires treatment before consumption.

Brackish and seawater (S.6 Brackish water, seawater) are water resources with high salt contents and as such are alternative water sources that require desalination before consumption. Usually, they are only used when other water sources are not available or access is limited.

Water can be harvested from fogs under favorable climatic conditions. Currently applications are limited to only a few areas and pilot scale, but the field is growing. Fog is not considered as a separate water source in this section, but some information can be found in the reference section.

Water is needed to carry out activities other than drinking or cooking and, particularly in water-scarce areas, communities often do not differentiate between water for domestic and non-domestic uses. Thus, the water supply systems in water scarce areas or areas with extended dry periods should be designed with multiple water uses in mind. Multi-use water supply systems are more likely to achieve an impact and be maintained over the long-term.

When selecting any kind of water resource, an initial assessment should be conducted that considers local factors, including the following (see Annex 2 for more information).

- **Water quantity:**
Is the yield sufficient throughout the entire year?
Can changes in water availability and water demand be estimated?
- **Water quality:**
How is water quality affected by local activities (e.g. sanitation practices, agriculture, industry, or other contamination sources in communities)?
- **Technology required for exploitation:**
Which technologies are required for abstraction and treatment and are they feasible? Are the required skills and technologies available for water source exploitation? Are appropriate and reliable supply chains in place for replacement parts and consumables (e.g. chemical additives, laboratory testing equipment)? Are the costs of water resource exploitation affordable?
- **Energy:**
Is pumping needed, or can gravity be used? If pumping is needed, are reliable and affordable energy sources available?
- **Acceptance:**
What are legal and social rights around the water source and are there cultural preferences for certain resources?
- **Environmental and health risks:**
What is the impact of water source exploitation on the population, environment, and ecosystems in its catchment?

S.1 Rainwater

Applicable to systems 1, 4	Management level –	Local availability –	Technology maturity level –
-------------------------------	-----------------------	-------------------------	--------------------------------



Rainwater refers to water that falls in drops from clouds to the earth's surface.

Rainwater can be collected from courtyards, hill slopes, institutional buildings, roofs of buildings in residential areas, or from temporary surfaces created by using cloth or plastic sheets, and it is stored in storage tanks or reservoirs (see I.1 Roof water collection system, I.2 Rainwater catchment dam, I.3 Sand/subsurface storage dam and System 1 Rainwater harvesting). Rainwater harvesting often supplements existing water resources when they become scarce or are polluted. In rare cases, it is used as a sole source of drinking-water when other sources are not available, not accessible, saline, or contaminated. Rainwater can be used for various purposes including gardening, irrigation, and domestic uses as well as for drinking-water. Additionally, it can be used to recharge groundwater through managed aquifer recharge techniques.³

Applicability and adequacy

In general, rainwater is mostly of good quality but can deteriorate during harvesting, storage, and use. Pathogenic microorganisms can enter the rainwater harvesting system through animal excrement (e.g. bird droppings). Also, inadequate rainwater collection and storage systems may be vulnerable to the intrusion

of surface run-off containing faecal contamination. First-flush devices, which prevent the first flush of run-off from being collected in storage tanks, are necessary for roof water collection systems (see I.1 Roof water collection system). When exposed to light and with sufficient nutrients, algae (cyanobacteria) may grow in storage tanks, which can produce compounds with unpleasant taste and odour, and under certain conditions, toxins which may impact health.

Rainwater can be slightly acidic (pH 5–6) because it interacts with carbon dioxide in the atmosphere to form carbonic acid. Since rainwater is generally free from other sources of alkalinity and has no buffering capacity, more acidic water can cause corrosion, such as of metal roof catchment areas. The roofing materials (e.g. paint coatings, metals) and storage tank materials can affect the water quality as well, leading to elevated levels of chemical contamination.

Rainfall quantities and patterns ("seasonality") and the size of the rainwater capturing area (e.g. roof) determine the rainwater harvesting yields at a given time of year.

Unless the existing water resources are extremely scarce, rainfall should be at least 300 mm/year to make rainwater harvesting a feasible primary drinking-water source.

Health and environmental aspects/Acceptance

Rainwater lacks minerals like calcium and magnesium, and thus lacks a particular taste. During storage, rainwater can develop taste and odour, which may negatively affect its acceptance as a drinking-water resource.

The introduction of contamination, such as faecal contamination from surface run-off, can pose further health hazards, which can be minimized by a well-designed and properly maintained rainwater harvesting system (see I.1 Roof water collection system) and point-of-use treatment solutions (e.g. H.4 Chemical disinfection and H.9 Solar water disinfection).

⊕ Advantages

- Easily available and accessible
- Rainwater is generally of good quality if properly collected, stored, and supplied

⊖ Disadvantages

- Supply is limited by rainfall patterns over the year, the size of the rainwater capturing area, and storage capacity of the rainwater harvesting system
 - Contamination of rainwater by air pollution, animal excreta, insects, dust, bushfire deposition, etc. is possible
 - Acceptance can be hampered due to a lack of taste or development of taste and odour during storage
-

→ References and further reading materials can be found on page 205.

³ Managed aquifer recharge is not considered in the intake section. An overview of issues and technological options can be found in Casanova, Deveau & Pettenati (2016).

S.2 Groundwater

Applicable to systems
4, 5, 6, 7, 8

Management level

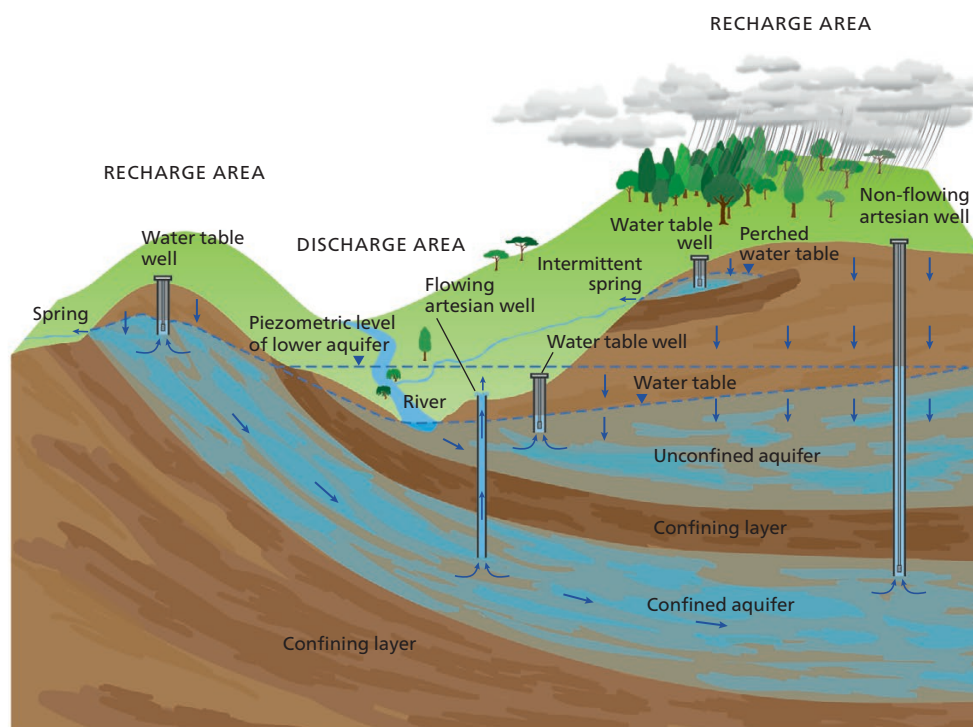
–

Local availability

–

Technology maturity level

–



Groundwater is fed by rainwater and from surface waters, such as rivers, streams, lakes, or wetlands, which infiltrate into the subsurface.

Groundwater is stored in cracks and voids in soil, sand, and rocks. These water-bearing subsurface layers are called aquifers. In the subsurface, water flows at different speeds depending on the size of the voids in the soil or rocks (porosity) and how well these spaces are connected (hydraulic conductivity). Subsurface groundwater is present in two zones: in unsaturated (or vadose) zones, voids are partially filled with water, while in saturated zones voids are entirely filled with water. The boundary between these zones is referred to as the water table, which fluctuates as a function of the balance between groundwater inputs and extraction. The water table can thus occur at various depths over time.

Aquifers can be confined or unconfined. Confined aquifers are found in between two layers of soil with a low permeability, such as rock or clay. Unconfined aquifers are underneath permeable soil layers and are directly recharged by rain or stream water.

Aquifers can be further distinguished between deep or shallow, and this affects how groundwater can be withdrawn through wells (see I.5 Protected dug well and I.6 Protected borehole)

Applicability and adequacy

Groundwater quality depends strongly on the geological conditions, location in relation to point and diffuse sources of contamination, adequacy and type of extraction technology, depth of the aquifer, and any existing protection measures.

In general, groundwater can be considered less vulnerable to contamination than surface waters. When water slowly infiltrates into the soil and travels through the subsurface within aquifers, it is naturally filtered, which may result in the removal of microbial contaminants, such as bacteria, viruses, and protozoa. However, shallow aquifers near the earth's surface are likely to be influenced by contaminated surface water bodies, on-site sanitation systems, landfill discharges, and industrial chemicals, such as pesticides, etc. Karst aquifers are also prone to contamination due to their large voids and high groundwater flow velocities that

therefore limit filtering capacity. Deep groundwater, protected by a confining layer, is generally better protected from microbial and chemical contamination.

In certain regions, groundwater may be affected by geogenic contamination. High levels of fluoride, arsenic, iron, manganese, or chloride can have either man-made or natural causes, and regardless have to be removed by multi-stage treatment technologies (see System 7 Groundwater subjected to geogenic contamination). An extensive overview of potential contaminants in groundwater catchments is given in the WHO publication (2006) *Protecting groundwater for health*.

Health and environmental aspects/Acceptance

Groundwater is usually well accepted as a drinking-water source, especially since it is often perceived as being less contaminated than surface water sources. However, while this is generally true, the safety of untreated groundwater sources is not guaranteed. Disinfection of groundwater sources may be needed where there is a risk of microbial contamination, particularly where aquifers are shallow, unconfined, karstic, or are known to be impacted by contamination.

Abstracting groundwater from a well at rates exceeding the recharge rate may decrease the level of the water table. If such overextraction continues for long enough, the well may eventually run dry. Overextraction may also increase the potential for drawing potential contaminants into the aquifer, such as salt water. Therefore, it is crucial to ensure that extraction rates do not exceed recharge rates for sustainable water supplies. Details on sustainable groundwater extraction, including measurement techniques and methods for understanding the magnitude of groundwater depletion, can be found in the International Union for Conservation of Nature and Natural Resources (IUCN; 2016) publication *Managing groundwater sustainably* (Smith et al., 2016).

⊕ Advantages

- Groundwater is often available close to where it is required
- Better microbial and chemical water quality compared to surface waters

⊖ Disadvantages

- Risk of natural contaminants, such as arsenic, fluoride, manganese, and iron, in certain regions
 - Accessing this water resource requires extraction technologies, such as constructing a well and installing a pumping system
-

→ References and further reading materials can be found on pages 205 and 206.

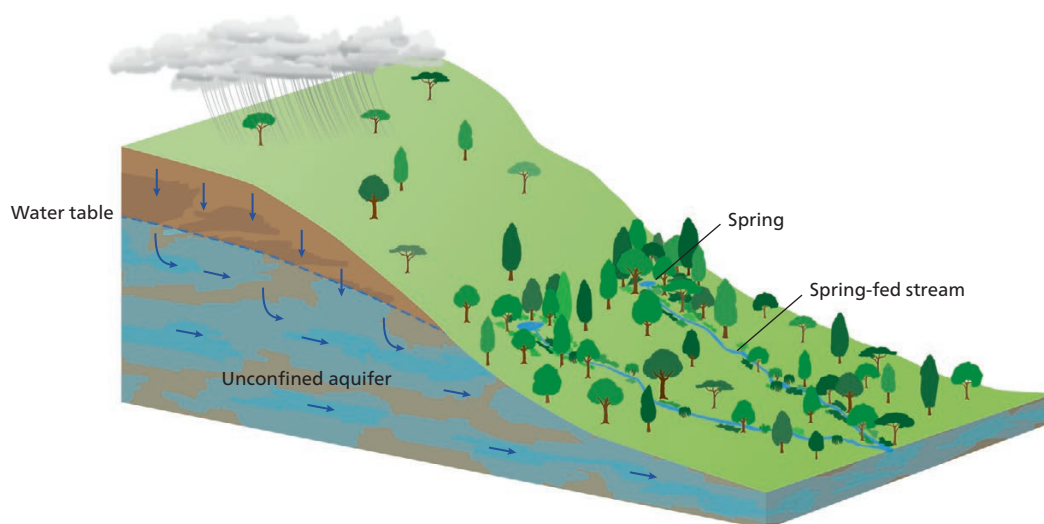
S.3 Spring water

Applicable to systems
4, 5, 6, 7, 8

Management level
–

Local availability
–

Technology maturity level
–



A spring is groundwater naturally flowing from the earth's subsurface to the surface.

A spring forms due to the pressure in an aquifer, which causes some of the water to flow out at the surface. Pressure is built if groundwater encounters a low permeability zone that hampers its flow. Ultimately, the water spreads laterally and intersects the earth's surface. This commonly happens at places where the topography is lowered in relation to the water level, such as at low elevations, along hillsides, on the side of a canyon or gorge, or at the bottom of slopes.

Some springs consist only of droplets of water seeping from the ground, while others are large and may create rivers or lakes. Gravity springs occur when groundwater meets an impermeable soil layer (such as clay) and is then forced to the surface. Artesian springs form when groundwater is trapped between two impermeable layers, thereby putting pressure on the groundwater. If there are cracks or fissures in the overlying soil, water is forced to flow through these openings up to the surface. Artesian springs can reach the surface with considerable pressure.

Applicability and adequacy

Springs can form in many landscapes, but locating them requires practical experience. Compared to other drinking-water resources, tapping springs may be relatively inexpensive in terms of construction and maintenance costs, particularly if the source is located close to consumers. Spring sources may be more shallow than wells or bores and there is generally no need for costly pumping or extensive abstraction infrastructure (although installation of a spring box may be needed). Since springs are generally located on hills, a simple gravity flow distribution system can be installed.

To maintain water supply and water quality, spring water should be properly tapped and spring protection has to be ensured. Water tapping from springs differs between artesian and gravity springs (see I.4 Protected spring intake).

Health and environmental aspects/Acceptance

Springs are commonly used sources of water that are well accepted by communities.

Depending on the local geological conditions, location, catchment activities, and existing catchment protection measures, spring water can generally be of good quality. However, as the spring approaches the ground, it can be subject to contamination (i.e. both at the spring outlet and in its direct vicinity). Major sources of contamination may include surface water run-off, infiltration with water contaminated from open defecation, inadequate on-site sanitation systems, and presence of animal faeces in the local vicinity.

A spring box (spring water collection chamber) is commonly installed to reduce the risk of contamination of the spring at the “eye” (see I.4 Protected spring intake). Where there is a risk of microbial contamination, the spring water should be disinfected (e.g. T.2.1 Chlorination in the case of piped distribution systems or H.4 Chemical disinfection for the household level).

⊕ **Advantages**

- Likely to have good water quality if spring catchment is properly protected and spring is properly tapped
- Low construction costs for tapping the water
- Can be used for relatively simple gravity water supplies without pumps

⊖ **Disadvantages**

- Quantity of water from springs can be susceptible to seasonal variation and water table fluctuations
 - Depending on soil structure and surrounding conditions, rainfall events can affect turbidity and microbial contamination
 - Springs occur only under specific hydrogeological conditions, and the location of the spring may not be easily accessible (e.g. on steep hillsides)
-

→ References and further reading materials can be found on page 206.

S.4 Rivers and streams

Applicable to systems
2, 3, 4, 8

Management level

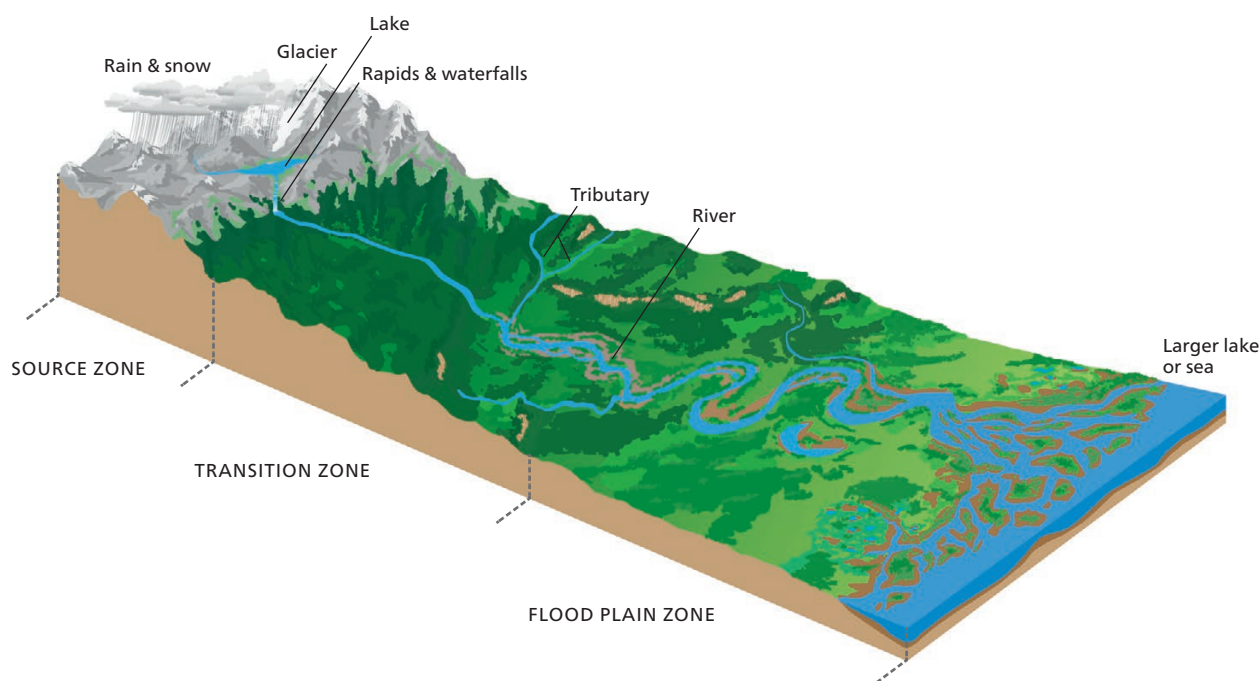
–

Local availability

–

Technology maturity level

–



A river or stream is a natural flow of freshwater across the land and subsurface towards another stream, river, lake, or the sea.

A stream is a water body that is in constant motion. Streams vary substantively in their characteristics, such as size, depth, velocity, salinity, and location. Thus creeks, brooks, tributaries, bayous, and rivers are all categorized as streams. Rivers are the largest type of stream, and they carry large amounts of water from higher to lower elevations.

A catchment area of a river is the area from which a particular river receives surface flow (e.g. from other rivers), subsurface water (e.g. from aquifers), and drainage water originating from precipitation. The term “upstream” refers to the direction towards the source of the river (source zone), and the term “downstream” refers to the direction towards the mouth of the river where it empties into larger rivers or the sea (flood plain zone).

Throughout the river’s course, the water transported downstream is in constant interaction with aquifers (see S.2 Groundwater), and the total volume of a river

changes in response to this underlying groundwater system. Many rivers and streams gain water from and/or lose water to groundwater during their course. Seasonal variations in water flow are expected for all rivers. Some may also dry completely during dry seasons or flow only in the subsurface. Periodically, as a result of heavy rain or increased snowmelt, the increased run-off leads to flooding of the downstream flood plains.

Applicability and adequacy

Rivers are multiple-use resources. In addition to household drinking and domestic water use, rivers are also used for irrigation, animals, small industries, transport, and ecosystem services.

The total quantity of water available at any given time is an important consideration when opting for a river water supply. Streamflow data might be available in water department offices or can be measured.

River water quality is highly variable by nature due to the type and intensity of surrounding land use, types of rocks and soils, and catchment vegetation and climate. Contamination of river water is likely due

to poor sanitation practices (e.g. open defecation, discharge of raw or inadequately treated sewage), surface run-off from surrounding agriculture and other anthropogenic activities, and/or industrial discharges. An extensive overview of potential hazards in surface water catchments and their management is given in the WHO publication (2016a) *Protecting surface water for health*.

In most cases, the quality of river water in medium- to small-sized or fast-flowing rivers does not differ much across the width and depth of a riverbed. In large, slow-flowing rivers, considerable variation in organic matter content, nutrients, and dissolved oxygen can be expected. River water intakes should ideally be upstream of any potentially contaminating activities from human settlements, agriculture, industry, or roads. (see I.7 River and lake water intake and I.8 Riverbank filtration). Upstream rivers, close to the source zone, can be relatively free of contamination, but in most cases, river water requires extensive treatment (see System 4 Freshwater sources and System 7 Groundwater subjected to geogenic contamination). In the rainy season, rivers might have low dissolved solid concentrations but large sediment loads that require removal to ensure effective disinfection.

Health and environmental aspects/Acceptance

Establishment of riparian buffer zones (strip of vegetation between the land and water body) can help reduce the impact of contaminated surface run-off, and restricting water body uses can reduce the impacts of potentially contaminating activities (e.g. bathing, washing, fishing, boating, etc.).

Water from slow-flowing rivers might have an unacceptable taste (e.g. moldy, musty, or earthy) from microbial compounds (e.g. cyanobacteria) that are not easily removed by standard water-treatment technologies.

In the presence of high organic matter content, chlorination (see T.2.1 Chlorination) can produce disinfection by-products, which should be minimized due to the potential health concerns associated with their long-term exposure. However, the longer-term potential health risks from these by-products are low in comparison with the confirmed acute risks associated with inadequate disinfection. Therefore, disinfection should not be compromised in attempting to control disinfection by-products (WHO, 2022a).

If water is used for a certain purpose in one location, it might affect users in another downstream location, causing conflicts or affecting the broader ecosystem. When proportionally large volumes of water are planned to be withdrawn from a river, integrated water resource management principles should be applied locally. It should always be taken into account that the development of water resources through dams

or abstractions in many cases leads to degradation of the aquatic ecosystem with numerous negative consequences (e.g. decline in biodiversity, mosquito breeding, etc.).

⊕ Advantages

- Typically easily available and accessible
- Quantity of water and seasonal variability are easier to assess than in other sources

⊖ Disadvantages

- Water quality is usually poor (microbial and chemical contamination, suspended particles) and extensive multi-stage treatment is needed
 - Seasonal variations in water quality and quantity
 - User conflicts due to competition for limited water resources in certain settings
-

→ References and further reading materials can be found on page 206.

S.5 Ponds, lakes, and reservoirs

Applicable to systems
2, 3, 4, 8

Management level

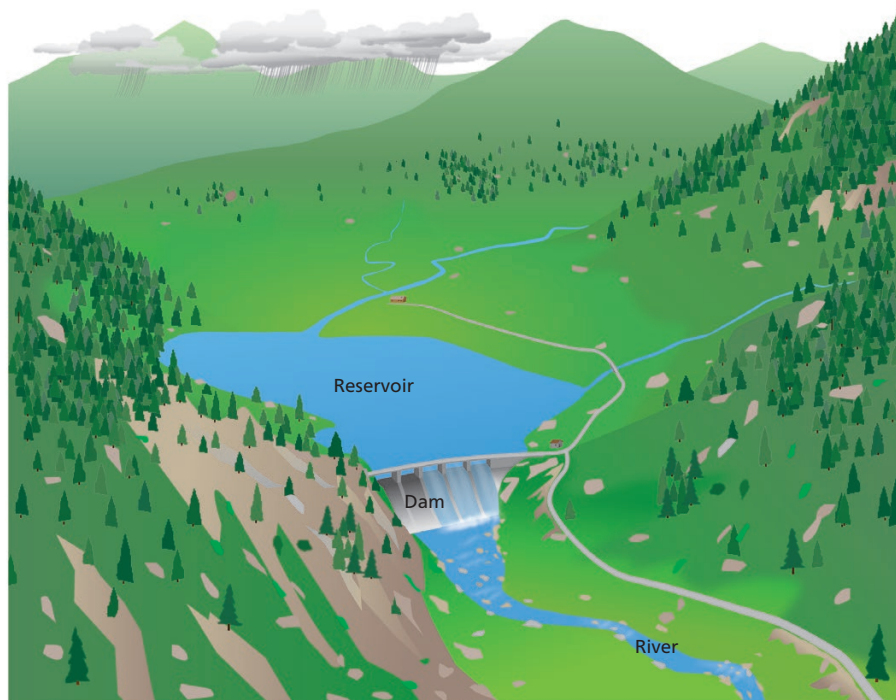
–

Local availability

–

Technology maturity level

–



Ponds, lakes, and reservoirs are standing or slow-moving surface water bodies that form naturally from rain, run-off, or river water.

Lakes and ponds are water bodies that may form naturally, reservoirs are always human-made. Reservoirs are built by constructing a dam across a river or part of a river where the flow of water is blocked to create a reservoir where water is stored (see I.2 Rainwater catchment dam).

When water is stored in reservoirs and lakes, losses through evaporation and seepage must be considered. Under dry tropical climates, annual evaporation rates of 1.2–2.5 mm/day are typical. In hot desert areas, annual evaporation may exceed 2500 mm. In cooler, more humid areas, annual evaporation is less than 1000 mm. Seepage rates depend on the ground permeability and retaining structures of the dam or lake. Depending on the size of the water body, shading may be appropriate to minimize evaporation losses (e.g. planting trees or covering with geotextile material).

Applicability and adequacy

Ponds and lakes are often multiple-use resources, and the water is used for irrigation, drinking-water for humans and animals, bathing, washing of clothes, small industries, and ecosystem services.

The quality of these surface water resources should be considered poor in most cases. In ponds, lakes and reservoirs, the water quality is influenced by contaminants from human activities, which can enter these water bodies through direct discharge, contaminated rivers and streams feeding these bodies, or through surface run-off. Microbial contaminants, can enter these systems through various pathways, including direct discharge of raw or inadequately treated sewage, through surface run-off impacted by faecal contamination from open defecation/inadequate sanitation facilities, agriculture, etc. An extensive overview of potential hazards in surface water catchments and their management is given in the WHO publication (2016a) *Protecting surface water for health*.

Standing surface water resources have a self-cleaning capacity. This means that under favorable

conditions, lakes and reservoirs can attenuate pollution by natural processes, such as microbiological degradation of certain compounds, inactivation of microorganisms by sunlight and/or predation, photolysis of some chemical pollutants, and sedimentation of particles and suspended solids (and contaminants sorbed to these particles). Cyanobacteria may be present under favorable conditions (e.g. certain nutrient concentrations and climatic conditions) and their scums may accumulate on the surface of ponds, lakes and reservoirs. This should be taken into consideration when locating an intake pipe (see I.7 River and lake water intake).

Health and environmental aspects/Acceptance

Ponds, lakes and reservoirs should be protected from contamination by preventing open defecation and discharges of inadequately treated wastewater through improved sanitation management measures. Establishment of riparian buffer zones (strip of vegetation between the land and water body) can help reduce the impact of contaminated surface run-off, and restricting water body uses can reduce the impacts of potentially contaminating activities (e.g. bathing, washing, fishing, boating, etc.). Due to the risk of contamination, surface water should always be treated (see System 4 Freshwater sources and System 7 Groundwater subjected to geogenic contamination).

The presence of cyanobacteria may result in taste and odour issues, as well as the presence of potentially harmful toxins. Stagnant water can be a potential mosquito-breeding site.

Accumulation of sediment may be an issue over time which requires management. These sediments may contain harmful microorganisms, metals and nutrients and certain climatic events can trigger a release of these contaminants from the sediment to the upper water columns, potentially causing a spiked deterioration in water quality and triggering cyanobacterial blooms.

Constructing a dam has major impacts on people living downstream of the river as well as aquatic organisms, plants, and domestic and wild animals. Biodiversity can be adversely (and sometimes irreversibly) impacted by the construction of dams. These impacts on people, aquatic organisms, and ecosystems should be assessed during the planning phase. Even for small dams, construction and planning should be controlled by respective authorities.

⊖ Disadvantages

- High contamination levels
- Deterioration in water quality after rain events (e.g. run-off containing microbiological contamination, turbidity)
- High water loss due to evaporation
- Stagnant water sources are potential mosquito breeding sites
- Might be difficult to obtain authorization to build a dam; high construction and maintenance costs
- Risk of cyanobacterial growth, which may affect water quality
- Often used for fishing, domestic (e.g. washing, bathing), and recreational activities (e.g. swimming, boating), which poses a risk to water quality

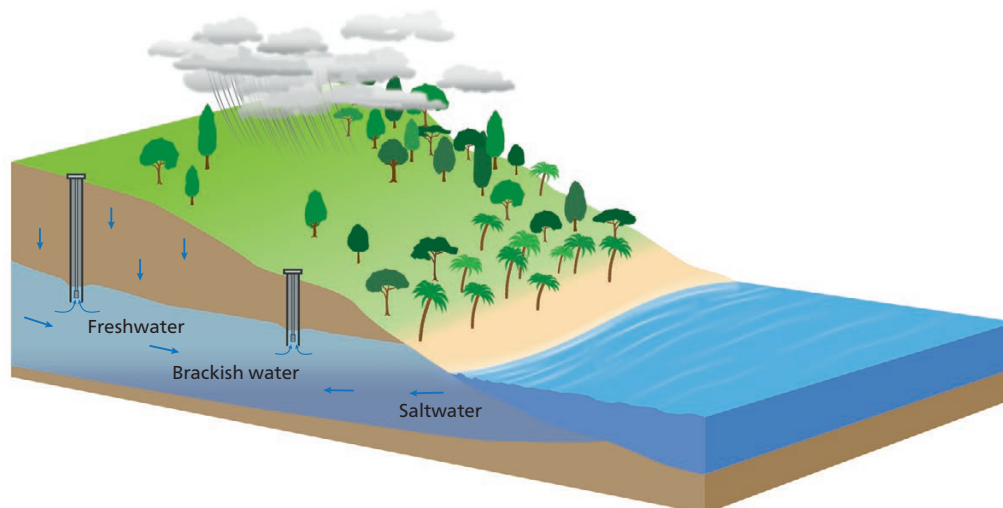
→ References and further reading materials can be found on page 206.

⊕ Advantages

- Lakes and reservoirs can provide year-round sources of freshwater that are easy to access
- Except during rain events or storms, water turbidity is often low at a certain distance from the shore

S.6 Brackish water, seawater

Applicable to systems 9	Management level –	Local availability –	Technology maturity level –
----------------------------	-----------------------	-------------------------	--------------------------------



Seawater comes from seas or oceans and has a high salt content. Brackish water is less salty than seawater but, compared to freshwater, has a salty taste and cannot be used directly for drinking-water purposes.

Seawater has a salinity of about 3.5%, meaning that every litre of seawater has 35 grams of dissolved salt (mainly sodium and chloride ions). The content of salt and other minerals in water sources is typically described in terms of the concentration of total dissolved solids (TDS). This gives seawater a TDS concentration above 35 000 mg/L, as compared to freshwater, which generally has a TDS concentration of less than 1000 mg/L. Brackish water forms by the mixing of freshwater with seawater and is characterized by TDS concentrations between 1000 to 10 000 mg/L. Brackish water can be found in estuaries (i.e. the inlet of a river into the sea or ocean) or aquifers. Brackish water can also be found inland in surface water (where there is a high evaporation rate that concentrates minerals in the water) or groundwater (where rocks in the aquifer have a high mineral content that leaches into the water).

In regions with limited freshwater availability, brackish water or seawater is used as an alternative water resource. To remove the high salt content from these sources, “desalination processes” must be applied (see T.5 Desalination). Common desalination techniques include thermal distillation (see T.5.1 Membrane distillation) and membrane separation (see T.5.2 Reverse osmosis). Using these technologies, salt water is converted into freshwater with very low concentrations of salt and other minerals. The removed salt and minerals are concentrated in a waste stream (“brine”).

Applicability and adequacy

Brackish water is sometimes used directly by communities that have no other alternatives. Seawater needs to be desalinated. Freshwater produced by thermal distillation and membranes is very pure and contains low concentrations of dissolved salts and minerals, such as calcium, magnesium, sodium, and chloride (TDS < 50 mg/L). This very pure water is commonly used for industrial or research applications. When producing drinking-water, certain minerals might be re-added (re-mineralization) to the purified freshwater to improve the taste and reduce corrosion in pipes, fittings, and tanks.

The use of brackish or saltwater as a source may be limited since desalination technologies require high amounts of energy. The treatment of seawater is more expensive than brackish water due to the higher TDS content. Additionally, brine disposal can be expensive. The total costs vary with the size and type of desalination system, the source water quality, and local energy costs, but overall costs to produce freshwater from saltwater are generally higher than making use of other water sources.

Health and environmental aspects/Acceptance

In addition to salt, brackish or seawater sources may contain harmful microbial and chemical contaminants, depending on local activities (e.g. discharge of human or industrial effluents). Contamination from marine cyanobacteria/algae may also impact source water quality. As such, treatment is needed prior to human consumption (see System 9 Desalination of brackish and salt water). For further information on drinking-water quality considerations for salt water, refer to WHO (2011) *Safe drinking-water from desalination*.

Desalinated water with a very low TDS content can taste unpleasant, which can result in low acceptance by consumers. The brine has very high salt concentrations and needs to be disposed of in such a way as to minimize environmental impacts. Options for brine disposal include discharging into the sea or ocean (in coastal areas), injection to a saline aquifer, or evaporation to produce solid salts. Because brine has a higher density than seawater, upon discharge into the ocean, appropriate measures (e.g. discharge only during strong sea currents or through nozzle diffusers) are needed to avoid the development of salty layers on the sea floor near the brine outlet, which negatively affect marine life. Any brine disposal must be in line with local environmental regulations and appropriate environmental impact assessments.

⊕ Advantages

- Abundant water source, easy to access if coastally located

⊖ Disadvantages

- High treatment and energy costs for freshwater production and brine management
 - Re-mineralization of produced freshwater might be necessary
-

→ References and further reading materials can be found on page 206.

In all improved water sources, water is collected from the source through an intake or withdrawal system. For each water source, there are various intake systems available. Some intake systems also act as a reservoir for storing water or provide a certain level of treatment.

This section describes intake systems that can be used for drinking-water supply, and it covers:

I.1 Roof water collection system

I.2 Rainwater catchment dam

I.3 Sand/subsurface storage dam

I.4 Protected spring intake

I.5 Protected dug well

I.6 Protected borehole

I.7 River and lake water intake

I.8 Riverbank filtration

I.9 Seawater intake

Rainwater collection systems differ depending on whether water is collected from the roof (I.1 Roof water collection system) and used as a supplementary water source during the rainy season or where water is collected from a larger catchment dam and it is used as a year-round water supply. Rainwater and/or surface water can be stored in a catchment dam (I.2 Rainwater catchment dam). Sand or subsurface storage dams (I.3 Sand/subsurface storage dam) can store and provide access to water flowing in the subsurface. Groundwater can be accessed at the outlet of a spring (I.4 Protected spring intake) or by constructing a well (I.5 Protected dug well and I.6 Protected borehole), which is an excavated hole extending down to the water-bearing formation. This hole should be supported (and protected from contamination) by a lining (for a dug well, I.5 Protected dug well) or a casing (for a borehole, I.6 Protected borehole). A variety of construction methods exist for building wells, the choice of which depends on soil characteristics, required depth and capacity, and the availability of tools and skills. Dug wells use traditional, simple, and widely accepted technology, which is generally lower in cost than drilled wells ("boreholes"). Compared to dug wells, however, the construction of

boreholes is often faster and safer, the risk of contamination is lower, and deeper groundwater sources can be accessed. Surface water intake structures vary depending on if the intake needs to be protected from rolling stones or debris (I.7 River and lake water intake), if the water level changes during the year, and if water pre-filtration through infiltration wells is performed (I.8 Riverbank filtration). Seawater intake structures (I.9 Seawater intake) have to adapt to ocean dynamics and should be designed not to harm the marine environment.

Properly constructed intake systems should both provide convenient access to water sources as well as protect water and its sources from contamination. See Annex 2 for a summary of technological interventions at the source.

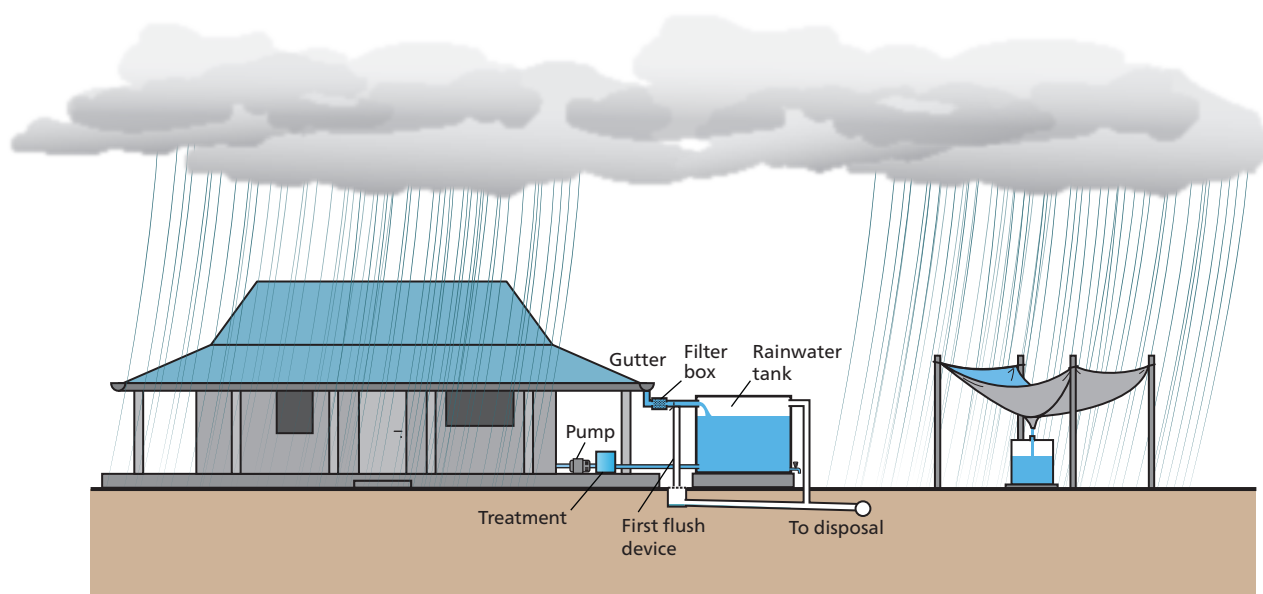
I.1 Roof water collection system

Applicable to systems
1

Management level
Household, school, health center, community

Local availability of technology or components
Mostly

Technology maturity level
Established technology



ROOF WATER COLLECTION SYSTEM

TARPAULIN COLLECTION SYSTEM

Rainwater is collected from a roof by a gutter and stored in a tank. Ideally, it includes a filter box to remove larger pieces of debris and a first flush device to redirect and discharge the first portion of roof run-off water that carries pollutants from the roof surface.

The main design parameters that must be considered for a roof water collection and harvesting system concern rainfall quantity and pattern, roof area, run-off coefficient, and storage tank volume in relation to water demand. The amount of rainwater harvested per year can be estimated using the following equation:

$$\text{Supply (L/year)} = \text{Rainfall (mm/year)} \times \text{Roof Area (m}^2\text{)} \times \text{Run-off coefficient}$$

A roof run-off coefficient is the ratio of the volume of rainwater that runs off the roof surface to the volume of rainwater that falls on that surface (this coefficient generally varies between 0.5–0.9). A run-off coefficient of 0.9 means that 90% of the rainfall is collected. This coefficient considers water losses due

to spilling, evaporation, wind, overflowing gutters, and leaky collection pipes and first-flush devices. The roof material also determines the run-off coefficient to a large extent and influences the quality of the harvested water.

Guttering is used to transport rainwater to the storage tanks and is available in different materials, such as plastic, metal (e.g. aluminum), bamboo, wood, etc. A gutter is fixed just below the roofline to catch rainwater run-off.

The first rainwater can collect dust, bird droppings, leaves, etc. lying on the roof surface. To prevent contamination of the storage tank, the “first flush” must be diverted. Roof water collection systems, therefore, should incorporate a first-flush device. These first-flush devices come in a variety of designs, generally consisting of a pipe or a tank into which the first rain flush is diverted. These systems are usually designed to collect run-off from the first 1–2 mm of rainfall. Once full, roof run-off flows to the main storage tank. A filter box upstream of the first flush device could also be used to protect against larger pieces of debris entering the water storage tank (e.g. leaves).

Plastic, metal, or ferro-cement tanks or clay pots and jars can be used to collect and store rainwater, and these can be located either on or below the surface of the ground. Ideally, storage tanks should provide a continuous supply to meet the demand for water throughout the dry season.

Applicability and adequacy

Rainwater harvesting is a flexible technology that can be applied under a wide range of conditions to supplement existing water resources. However, annual rainfall should be at least 300 mm/year to make rainwater harvesting a feasible option for supplementary water supply. It is rarely used as a primary or sole water source, but in such cases, large water-storage capacities are needed and water quality needs to be maintained over prolonged storage periods.

The capacity of the storage tank is determined by rainfall patterns throughout the year and the size of the rainwater catchment area (e.g. roof). Usually, the storage tank is the most expensive component of a roof water collection system, and the choice of tank depends on the range and price of locally available commercial options and the cost and availability of building materials.

The quality of rainwater varies depending on the harvesting method (e.g. roof material) and storage type. Some common problems include faecal contamination from birds and small animals or from humans and livestock (e.g. underground tanks), as well as lead contamination from roofs or chemical contamination from paintwork. Chemical contamination may also arise from locally polluting activities, such as industrial emissions, agricultural burning, and pesticide spraying.

Operation and maintenance

Roof water collection systems range in size and complexity. For larger, automated systems, some expertise is required for set up and installation. For low-technology systems, the operational expertise and maintenance is minimal and can be handled by the user. Implementing these systems should be accompanied by appropriate user education.

Apart from droughts, the main concern with roof water collection systems is the quality of the stored water. The quality should be controlled by diverting first flushes and by the occasional cleaning of the roof and gutters. In practice, the efficiency of many systems is greatly reduced by poorly installed or broken gutters. An uneven slope of the guttering should be avoided because of the formation of stagnant water pools that lead to vector breeding (e.g. mosquitos). Another typical problem is broken taps at the storage tanks. For implementing rainwater harvesting projects, the supplied tanks and taps must be adequate for

their level of use. Storage tanks should be securely covered to keep out insects, dirt, and sunlight, which promotes the growth of cyanobacteria and algae in the tank. Furthermore, taps should be installed above the base of the tank to avoid discharging settled debris.

Health and environmental aspects/Acceptance

Stagnant water in storage tanks can support mosquito-breeding sites if the tanks are not adequately covered.

Rainwater lacks minerals like calcium and magnesium, and thus lacks a particular taste. Additionally during storage rainwater can develop undesirable taste and odour, which may negatively affect its acceptance as a drinking-water resource. Most common taste and odour issues arise through small dead animals, sediments, biofilms ("slimes"), or algal growth in the storage tanks, which may also represent a health risk if this water is consumed.

Where there is a risk of microbial contamination, stored rainwater should be disinfected to inactivate bacteria and other microorganisms when it is used for drinking. This can either be done at the level of the tank (e.g. by chlorination) or directly before consumption using household water treatment (e.g. H.4 Chemical disinfection or H.9 Solar water disinfection).

⊕ Advantages

- No electrical energy is required if rainwater is collected by gravity and stored in elevated or ground-level tanks
- Low capital and operating costs
- Long service life
- Individual household ownership and use
- Water is often available where needed

⊖ Disadvantages

- May run dry during droughts and dry season
 - High contamination risk where there is poor operation and maintenance
 - For underground water tanks, a pump might be needed
 - Potential breeding area for mosquitos
-

→ References and further reading materials can be found on page 207.

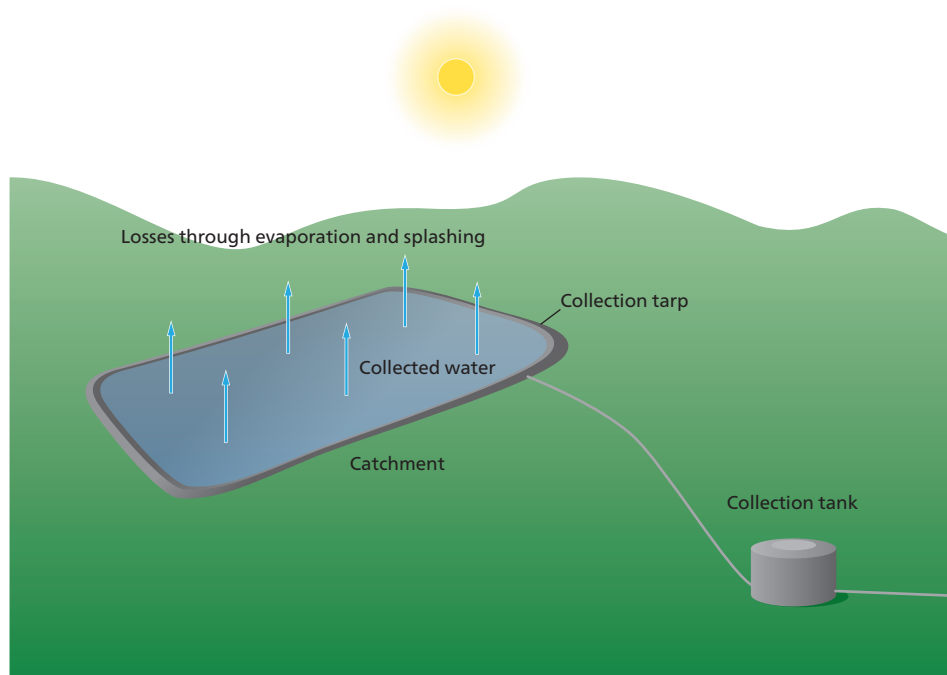
I.2 Rainwater catchment dam

Applicable to systems
2, 3, 4, 5, 8

Management level
Community, centralized

Local availability of technology
or components
Yes

Technology maturity level
Established technology



Constructing a dam across a natural rainwater catchment area, such as a valley, creates a stored-water reservoir available for human use.

Reservoirs are built by constructing a dam across a valley or drainage to block the flow of year-round or intermittent run-off water from rivers, streams, or springs to create a reservoir where water is stored.

The ideal site for a reservoir should allow for a large volume of water to be retained with the smallest dam possible (e.g. a wide valley that narrows suddenly). Dams without spillways are built for relatively small and constant stream water flow, whereas a spillway is constructed for relatively large streams with seasonal fluctuations. The dams are usually constructed upstream of all human settlements and potentially contaminating activities (e.g. agriculture, industry), where possible, to reduce the potential for water contamination. After choosing a site for a dam, the height of the dam is approximated relative to the desired water storage volume of the reservoir and water losses by seepage and evaporation. A guide for calculating water storage, dam height, and thickness as well as other important design considerations can be found in the

Food and Agriculture Organization of the United Nations (FAO) publication *Manual on small earth dams. A guide to siting, design and construction* (2010).

For small earthen dams (<3 m in height), banks can be constructed using earth with a suitable clay content that are reinforced with masonry or concrete. Dams >6 m in height are not considered here, as they require more complex engineering and experience. Dams of >3 m might be required in hot climates (i.e. high evaporation rates) with seasonal rainfall to store enough water for the entire year.

Users can abstract water directly from the reservoir or the water can be supplied (pumped or gravity-driven) via steel or concrete pipes to covered storage tanks or through a larger distribution system to households. A valve is usually installed at the outlet of the dam to control water flow in the pipes. Water from reservoirs requires multi-stage treatment before it is safe for consumption (see System 1 Rainwater harvesting).

Applicability and adequacy

The storage capacities of dams can vary widely depending on the water demand and the site where

the dam will be built (e.g. site-specific geology, topography, annual rainfall, etc.).

Water losses can occur due to evaporation and seepage (water loss due to infiltration through porous soil). To prevent seepage, small reservoirs are usually lined with concrete, mortar, or impermeable clay.

Appropriate design, construction, maintenance, and inspection/monitoring of the dam are essential, since the risks to downstream populations can be considerable. These risks should always be considered during planning, as well. Even for small dams, construction and planning should be reviewed, approved, and controlled by appropriate authorities.

The life expectancy of a properly designed earth dam is > 10 years, which can be extended through maintenance and rehabilitation as needed.

Operation and maintenance

There should be standard operational procedures in place to manage the controlled release of water during heavy rainfall events to avoid over spilling and the uncontrolled release of water downstream, as well as to protect the integrity of the dam. Sediment transported by rivers or streams can also reduce the storage volume of the reservoir and act as a sink for contaminants (such as microorganisms, metals, and nutrients). Therefore, sediment should be occasionally removed.

If the water is not extracted directly by the water users from the reservoir, a local community member should be appointed to open and close the valves of the dam to regulate the water flow. The outlet pipes and valves should be checked regularly for leaks.

Routine dam integrity inspections should be conducted to minimize risks from dam failure.

Health and environmental aspects/Acceptance

Generally, water quality is expected to be poor for surface water dams and open storage facilities, such as reservoirs, due to multiple contamination pathways. The impact on populations and ecosystems at the location of the dam, and upstream and downstream of the dam, should be assessed during the planning phase.

The stagnant water can be a potential mosquito-breeding site. Certain fish species, such as tilapia, live on insect larvae and could be introduced into the reservoir to control mosquitos. However, increased nutrient content and faecal contamination from fish should be taken into account in such cases, as well as the potential impact of any introduced species on aquatic ecosystems. Water circulation (e.g. solar-powered pumps to gently circulate water) can limit water stagnation as well as cyanobacterial growth.

The presence of animals or improper sanitation facilities in the catchment can lead to water contamination, and watershed protection measures are indispens-

able for ensuring water safety for multiple uses. Fencing the dam and reservoir can prevent livestock access and reduce the risk of faecal contamination. Water safety plans can help to ensure adequate protections are implemented (see X.5 Water safety planning).

+ Advantages

- Reservoirs can provide year-round freshwater storage while facilitating easy access
- Costs for constructing a small earthen dam are usually low (locally available material)

- Disadvantages

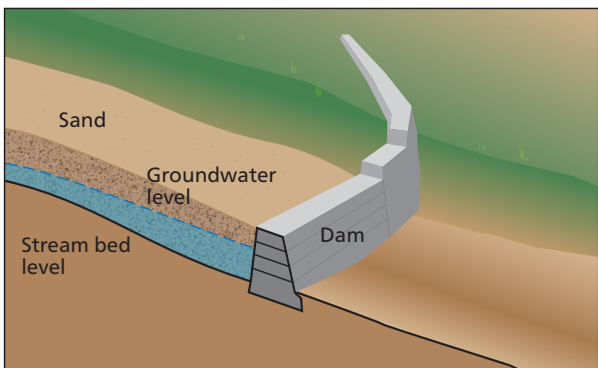
- High contamination risk for reservoirs, which may also be potential mosquito-breeding sites
 - High water loss due to evaporation
 - Authorization needed from authorities to construct and build dams
 - Possible impacts on water availability for nearby and downstream populations; possible conflict
 - Possible negative impact on the ecosystem
 - High risk to downstream human safety and property in the event of dam failure
-

→ References and further reading materials can be found on page 207.

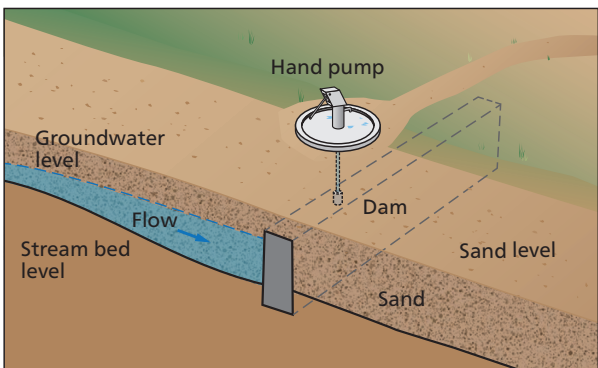
I.3 Sand/subsurface storage dam

Applicable to systems 4	Management level Community	Local availability of technology or components Yes	Technology maturity level Established technology
----------------------------	-------------------------------	--	---

SAND STORAGE DAM



SUBSURFACE STORAGE DAM



Sand storage dams and subsurface storage dams are built in arid areas to trap water during the rainy season and store it for use in dry periods. Sand storage dams are constructed above ground, whereas subsurface storage dams are built entirely underground.

The general principle of sand and subsurface storage dams is similar, as both store rainwater, which can then be used during dry seasons for various purposes (e.g. for livestock, irrigation, domestic use, and drinking-water).

Sand storage dams are constructed on the surface and tap into the bed of a seasonal river. These dams are usually only slightly higher than the upstream river bed. During rainy periods and high river flow, sand and soil particles are transported and deposited in front of the dam. Run-off water is stored in these deposits as groundwater. Each time the reservoir fills with sand, the crest of the dam can be raised for more water storage. Water is commonly abstracted by scoop holes in the riverbed, by wells, or by laying a perforated outlet pipe at the bottom of the dam that is connected to a tap on the other side of the reservoir. Protected wells with hand pumps (see I.5 Protected dug well) are recommended abstraction structures, since scoop holes are very susceptible to pollution from

animals and humans, and outlet pipes with a tap could weaken the dam structure if not properly constructed.

Subsurface storage dams are built entirely below the ground, where they hinder the flow of groundwater. The crest of the subsurface dam is recommended to be 1m below the surface to prevent the land from becoming waterlogged. Water from this reservoir can be abstracted through a protected dug well, or where appropriate (e.g. at slopes of hills), by placing a gravity pipeline through the dam.

The main advantage of both sand and subsurface storage dams is that the stored water is protected against evaporation and is naturally filtered by the soil, which may improve the water quality. Subsurface storage dams have less water-storage capacity compared to sand dams, which can be regularly raised. However, subsurface dams are less expensive and relatively easier to maintain as compared to sand dams.

Applicability and adequacy

Sand storage dams are preferably used at sites with steep slopes, whereas subsurface storage dams are built in flat areas.

The thickness and height of the dams depend on site-specific factors, such as the total streamflow of the groundwater or seasonal river. In a first step, a trench is dug across the river bed down to an impermeable

and solid soil layer, such as rock. Walls are then constructed in the trench, and the dam is built from locally available materials, such as blocks and stones, concrete, or earth.

For both dam types, wing walls, which are walls that may be added at an angle to direct and confine the flows, should be embedded in the river bank to prevent erosion. The downstream side of the dam should be reinforced with concrete or large boulders. Water losses through cracks in the impermeable soil base can occur.

The lifespan of properly designed subsurface storage dams may be over 50 years. Sand storage dams may require yearly rehabilitation or raising, e.g. after floods or due to the accumulation of sediments and sand.

More information on technical design considerations and the construction of groundwater dams can be found in the *Vétérinaires Sans Frontières* publication *SubSurface dams: a simple, safe and affordable technology for pastoralists* (2006).

→ References and further reading materials can be found on page 207.

Operation and maintenance

If properly constructed, these storage structures require only minimal operation and maintenance activities. The wells (see I.5 Protected dug well) and gravity pipes should be cleaned regularly. After floods, sand dams have to be checked for potential damage, and any issues should be repaired immediately by suitable technical experts.

Health and environmental aspects/Acceptance

Groundwater dams impact downstream groundwater flow and recharge, which needs to be considered during the planning phase. Although the quality of water abstracted from sand dams and subsurface dams may be somewhat better than that of river water due to natural filtration processes, some contamination is still likely, and treatment is advisable.

⊕ Advantages

- Storage of seasonal water resources
- No loss of stored water through evaporation
- Typically better quality than surface water due to natural filtration
- Durable and inexpensive structures can be constructed with locally available materials, such as earth and stone, concrete, blocks, etc.
- Little operation and maintenance required – silting is not a problem for groundwater dams

⊖ Disadvantages

- Construction of a dam requires expertise and is labor-intensive
- Suitable construction sites may be far from water users

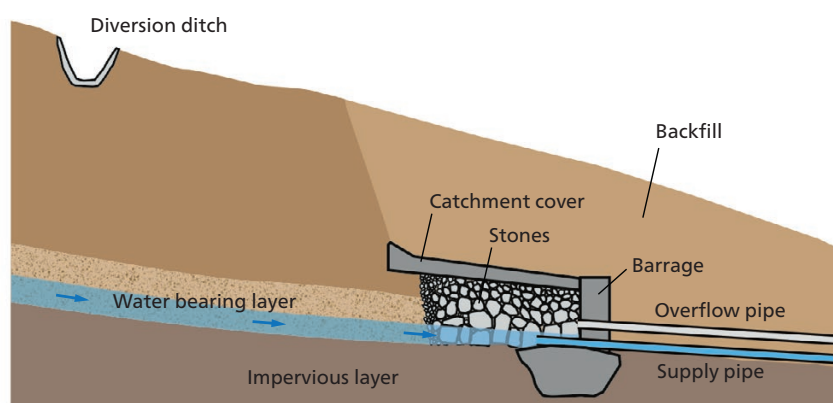
I.4 Protected spring intake

Applicable to systems
4, 5, 6, 7, 8

Management level
Community

Local availability of technology
or components
Yes

Technology maturity level
Established technology



Spring water collection systems are constructed to catch spring water, facilitate its collection, and protect it from contamination.

Depending on the type of spring (see S.3 Spring water) the intake structures can differ.

For gravity springs, a spring box (or spring chamber) is usually installed. Although there are many different designs, there are a few common features shared by most of them. Spring boxes are structures made out of concrete, bricks, or clay. They are permeable on one side or at the bottom to allow spring water to collect and are watertight on all other sides. Spring boxes with an open bottom are more typical for springs in flat areas and are usually easier to construct.

The role of the spring box is to prevent infiltration and mixing of surface run-off water with spring water. As such, spring boxes should have a secure but removable cover, which provides access for maintenance but prevents rainwater or surface water from penetrating. The spring box has an outlet pipe and an overflow pipe with a screen to prevent mosquitos and small animals from entering. Some erosion control measures are required at the overflow pipe to protect the structure. To avoid surface run-off entering the spring box, a run-off diversion ditch is installed, typically a few metres upstream (upslope).

Large trees or other deep-root vegetation might damage the spring box structures over time and should therefore be avoided when construction sites are selected. Spring boxes may be designed to accommodate a large storage capacity and can thus also serve as a storage tank. When high amounts of suspended solids are expected to affect the spring water quality, spring boxes can also be designed to serve as a sedimentation tank.

Further detailed design, construction, operation, and maintenance considerations on spring intake structures are given in the Swiss Centre for Development Cooperation in Technology and Management (SKAT) publication *Spring catchment* (Meuli C & Wehrle, 2001).

Applicability and adequacy

Spring water collection systems are simple and robust in design and require no pump for water abstraction. As such, they are relatively cheap compared to other intake technologies. Spring boxes can be built from locally available material, such as masonry and concrete. They can be easily modified to fit local needs and environments or combined with other technologies, such as gravity-driven water distribution systems.

Establishing inner and outer protection zones can shield the spring from pollution. An inner protection zone around a spring (with a minimum radius of 15 m) is

recommended.⁴ It can be formed by constructing fences or barriers to keep away grazing animals, which can contaminate spring water with their feces. To avoid other polluting human activities, such as the construction of latrines, application of manures, fertilizers or pesticides, etc. in the nearby area, extended protection zones (minimally extending to where the groundwater is at least 2 m deep or 30 m away from the eye of the spring) should be built.⁴ Within the inner protection zone, only grass or other light vegetation should be planted. Roots from trees or bushes could damage the spring box or block pipes. However, in the extended protection zone, trees and bushes that do not consume a lot of water are beneficial, since they prevent erosion and heavy run-off.

→ References and further reading materials can be found on pages 207 and 208.

Operation and maintenance

The infrastructure for spring water intake and abstraction does not require significant operation and maintenance. Regular monitoring of the intake elements as well as of the water quality should be conducted on a routine basis.

If a decrease in water flow is observed, it is likely that the collection system is clogged. Leaks at the spring box or at the supply and overflow pipes should also be identified and repaired. An increase in turbidity during storm events could indicate contamination from surface run-off. Sediment removal from the spring box is required. Periodic (e.g. seasonal and after flooding events) disinfection of the spring box may also be required. It is advisable to measure the flow of the spring and compare the results to the same season in previous years to estimate the reliability of the spring.

Health and environmental aspects/Acceptance

Springs are usually very well accepted by users. The location, geological conditions, and protection measures in place will influence the water quality (see S.3 Spring water). Where there is a risk of microbial contamination, spring water should be disinfected prior to consumption (e.g. H.4 Chemical disinfection).

⊕ Advantages

- Low construction costs if no pumping is required
- Protection of spring water quality
- Spring box can also provide sedimentation basin and storage features
- Low operation and maintenance efforts/costs
- Usually well accepted

⊖ Disadvantages

- Depending on the type of spring, the water flow reliability will differ

⁴ General guidance only. Appropriate protection distances should be site-specific and consider local factors, including soil type and permeability, depth of the water table, and the volume and concentration of contaminants. For guidance on determining appropriate minimum safe distances for potentially contaminating activities, refer to WHO (2024a).

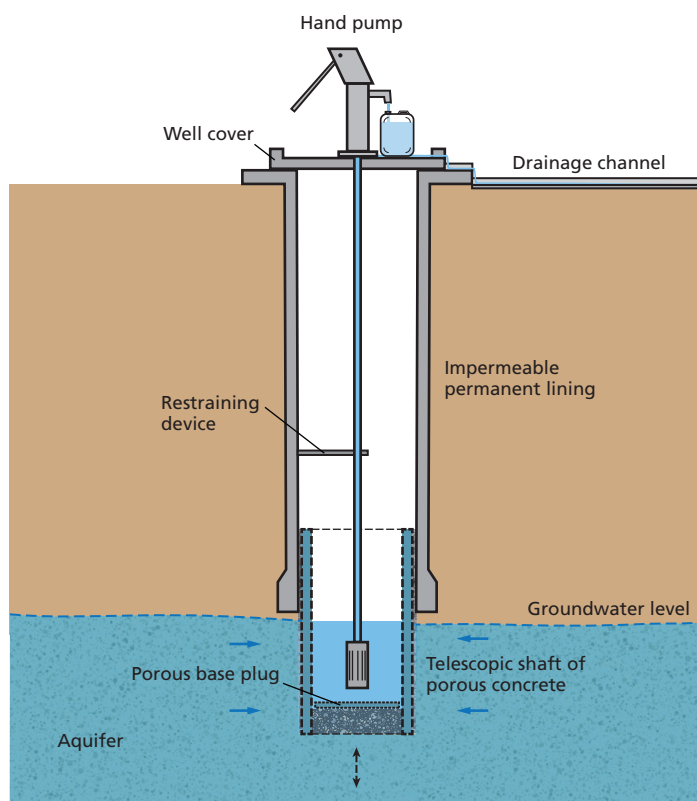
I.5 Protected dug well

Applicable to systems
4, 6, 7, 8

Management level
Community, household

Local availability of technology
or components
Yes

Technology maturity level
Established technology



A dug well results from excavating a hole in the ground from which groundwater can be abstracted with a pump or a bucket. A dug well is protected from run-off water by a well lining, a platform (apron), and a well cover.

Dug wells are traditional technologies used to extract shallow groundwater. They are often excavated manually (hand-dug well) and are large enough for persons to enter to maintain or deepen the well. Compared to drilled wells, such as boreholes (see I.6 Protected borehole), dug wells have much larger diameters, typically ranging from 0.8m up to 15m. Depths range from < 5m (shallow dug well) to > 20m (deep dug well). The soil type, diameter, and depth of the dug well determine the amount of water available for extraction. The deeper and wider a well, the higher the infiltration area and therefore the greater the rate of well recharge.

In many rural areas, unprotected dug wells are simple holes in the ground that can be easily contaminated by surface water run-off and/or excrement from humans or animals.

A protected dug well is protected from run-off water by a well lining that is raised above ground level, a platform (apron) that diverts spilled water away from the well, and a cover that prevents bird droppings and animals from falling into the well. The well head is the visible structure at the surface that is composed of a concrete seal, a well cover, a safe water-lifting device such as a hand pump, and a drainage channel. Under the well head is the well shaft and the intake area, where groundwater can be accessed by the pump. At least the top 3m of the well shaft should be lined to stabilize the well and ensure that surface water cannot penetrate directly into the well. But appropriate protection depth is site specific and normally the lining extends between 1–4m below the water table, where the depth achieved is dependent on how permeable the aquifer is compared to the rate of de-watering. The lining also needs to be extended above the ground level at a height that will prevent surface water infiltration. Common materials used to line wells above water level are bricks and mortar or concrete blocks or rings. The walls below the groundwater table need to allow groundwater to enter the well and are typically

made out of gravel, coarse sand, or porous concrete. It is advisable to use a design that easily allows for subsequent deepening. For this, best practice is to make the well shaft above the water table as a permanent lining that does not move, with a smaller diameter telescopic lining at the water table that can then be 'caissoned' (sunk while digging) into the water table. This allows the well to be deepened more easily at a later stage.

Besides properly lining and covering dug wells to maintain groundwater quality, protection of the surrounding area is important, such as by constructing fences to keep out grazing animals and avoiding other human activities that may introduce contamination. The accumulation and ponding of surface water near the well should be avoided by mounding earth around the well to improve drainage away from the well. To minimize the risk of contamination, the wells should be located away from contamination sources at a minimum safe distance appropriate for the local context.⁵

Further detailed design, construction, operation, and maintenance considerations on shallow dug wells are given in the SKAT publication *Hand-dug shallow wells* (Collins, 2000).

Applicability and adequacy

Dug wells are applicable in areas with suitable geological conditions. This includes settings with relatively high/shallow groundwater tables and appropriate substrata, such as clay, sand, gravel, and mixed soils without large boulders and rocks.

Protected dug wells can be a valuable alternative to unprotected water sources. They are usually not technically intensive to implement and can often be constructed through the involvement of the community. For the excavation and lining of a new well, circular well rings made of concrete are commonly used (see Collins, 2000).

After a new dug well is constructed, it must be disinfected with chlorine before use to remove any microbial contamination that potentially entered during the well construction phase.

Dug wells have minimal capital and maintenance cost requirements as compared to other types of wells.

Operation and maintenance

The communities using the wells should be involved in their operation and maintenance. Maintenance activities include checking the apron for cracks, improving the yield by deepening the well or removing infiltrated sand particles, and clearing drainage channels. Hand pumps and other lifting devices need to be checked regularly. The area around the protected dug well should be kept clean to avoid any contamination. Periodic (e.g. seasonal and after flooding events) disinfection of the dug well may be required (e.g. chlorination).⁶

Health and environmental aspects/Acceptance

Dug wells are usually accepted, and are a traditional method of groundwater abstraction in many areas. In terms of risks, the collapse of well walls during construction poses a significant risk. In deep dug wells, poor air quality during construction work can also be a risk, since the use of fuel-driven pumps for draining the well during excavation can lead to the accumulation of dangerous gases. Thus, ensure all pumps/generators are downwind and never lowered into the excavation.

Groundwater quality is highly dependent on local geological conditions, well location relative to sources of contamination, and protection measures in place. Although groundwater is often less turbid and less contaminated than surface water sources and is perceived to be safer, this is not always the case. Where there is a risk of microbial contamination, well water should be disinfected prior to consumption (e.g. H.4 Chemical disinfection).

The abstraction of groundwater through wells alters the groundwater level, and intensive extraction can have adverse effects on nearby water security as well as on the surrounding environment. Ensuring that extraction rates do not exceed recharge rates is crucial for a sustainable water supply. Details on sustainable groundwater extraction, including measurement techniques and methods for understanding the magnitude of groundwater depletion can be found in the IUCN publication *Managing groundwater sustainably* (Smith et al., 2016).

⊕ Advantages

- Low cost for construction, operation, and maintenance
- Construction materials locally available
- High acceptance

⊖ Disadvantages

- Long construction phase
- Excavation can be dangerous (collapsing of well walls)
- Fluctuations in water table affect yields from wells

→ References and further reading materials can be found on page 208.

⁵ For guidance on determining appropriate minimum safe distances for potentially contaminating activities, refer to WHO (2024a).

⁶ For guidance refer to *Technical notes on drinking-water, sanitation and hygiene in emergencies: cleaning hand-dug wells* (WHO & WEDC, 2013).

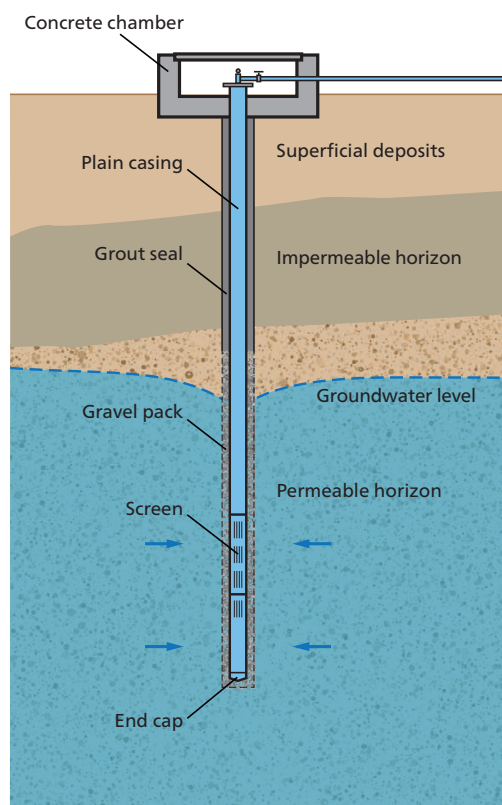
I.6 Protected borehole

Applicable to systems
4, 6, 7, 8

Management level
Household, community,
centralized

Local availability of technology
or components
Mostly

Technology maturity level
Established technology



A borehole for extracting water is a hole that is vertically drilled into the ground to reach groundwater bodies. Essential components of a borehole include a strong casing that prevents the walls from collapsing, a screen that allows groundwater to enter the borehole, a sanitary seal that protects the borehole from intrusion by surface run-off, and a manual or motorized pump that extracts groundwater.

Boreholes further differ from dug wells in their diameters, which generally vary between 0.1–0.25 m. Boreholes are typically made with hand-drilling technologies (such as hand augers, manual percussion, sludging, or jetting) and mechanical drilling equipment. Mechanical drilling technologies are capable of drilling up to 200 m deep, while manual drilling technologies can generally only access much shallower depths. Drilling technologies are described in detail in the SKAT publication *“Drilled Wells”* (Ball, 2000).

After drilling a borehole, several elements must be added before the source can be safely used, including:

- The well head and sanitary concrete seal prevent contaminants from entering the well.
- The well casing stabilizes the well against collapse and contamination. Steel and PVC pipes are normally used for well casings.
- The well screen holds back sediment while permitting water to enter the well. When the casings are made of PVC pipes, the pipes can be slit to create fine cuts that can serve a similar function.
- The gravel pack between the screen and the borehole is required when the soil grains are smaller than the screen mesh.
- A manual or motorized pump is required to abstract the water from the borehole.

Applicability and adequacy

Generally, the construction of boreholes is quicker and safer than dug wells, but requires more expertise.

Depending on the depth and diameter of the borehole and the infiltration area of the groundwater body, they can be designed for household, community, or centralized supply in urban and rural areas. The life expectancy of a properly designed borehole is > 20 years, which can be extended through maintenance and rehabilitation as needed.

The quality of groundwater depends on the local hydrogeology, its proximity to sources of contamination, the adequacy of protection measures in place (e.g. well casing, sanitary seal, slab/apron and walls, drainage channel, fencing, etc.), and the adequacy of the borehole's construction. Boreholes (extracting deep groundwater) are usually better protected from surface contamination than dug wells (abstracting shallow groundwater). Nevertheless, building a fence and/or roof around the well head is recommended. To minimize the risk of abstracting impaired groundwater, boreholes should be located away from contamination sources at a minimum safe distance appropriate for the local context.⁷ When choosing an appropriate location for a borehole, the local geology must be considered to assess if there is a risk of geogenic contaminants (e.g. arsenic, fluoride). In coastal areas, saltwater intrusion can become a problem, particularly if the rate of groundwater abstraction is too high.

Operation and maintenance

The operation and maintenance of boreholes include cleaning the apron and surrounding areas to prevent groundwater contamination. Maintenance and repair of the pump require training and access to suitable tools as well as replacement parts.

Periodic disinfection of the borehole may be required, e.g. chlorination applied seasonally and after flooding events.⁸

Health and environmental aspects/Acceptance

Although groundwater is often less turbid and less contaminated than surface water sources and is perceived to be safer, this is not always the case. Where there is a risk of microbial contamination, groundwater should be disinfected prior to consumption.

If boreholes are drilled into aquifers containing geogenic contaminants (e.g. arsenic, fluoride), the groundwater requires treatment before distribution (e.g. T.3.1 Fluoride removal methods, T.3.2 Arsenic removal methods) or use (H.10 Fluoride removal filters, H.11 Arsenic removal filters).

The abstraction of groundwater through wells alters the groundwater level, and intensive extraction can have adverse effects on nearby water security as well as on the surrounding environment. Details on sustainable groundwater extraction, including measurement techniques and methods for understanding the magnitude

of groundwater depletion, can be found in the IUCN publication *Managing groundwater sustainably* (Smith et al., 2016).

⊕ Advantages

- Boreholes tend to be less susceptible to contamination than dug wells
- Boreholes can be safer and quicker to construct than dug wells
- Less maintenance of the borehole
- Simple drilling technologies are available

⊖ Disadvantages

- Siting and drilling may require expertise and costly equipment depending on local conditions
- Pump maintenance requires expertise/training and access to tools/parts

→ References and further reading materials can be found on page 208.

⁷ For guidance on determining appropriate minimum safe distances for potentially contaminating activities, refer to WHO (2024a)

⁸ For guidance refer to *Technical notes on drinking-water, sanitation and hygiene in emergencies: cleaning and rehabilitating boreholes* (WHO & WEDC, 2013).

1.7 River and lake water intake

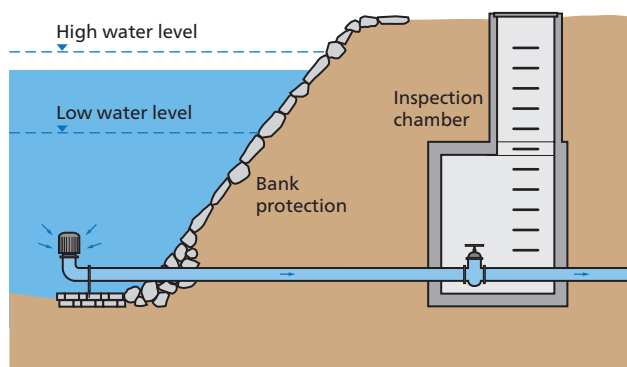
Applicable to systems
2, 3, 4, 8

Management level
Community, centralized

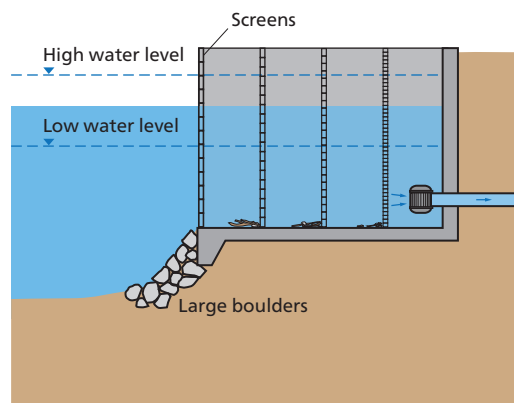
Local availability of technology
or components
Mostly

Technology maturity level
Established technology

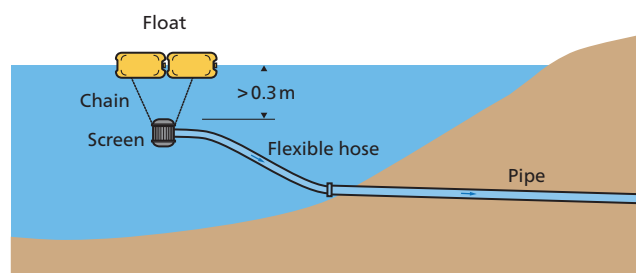
UNPROTECTED INTAKE



PROTECTED INTAKE



FLOATING INTAKE



River and lake intake structures are installations on or in rivers and lakes, which are needed to safely abstract water. Raw water is transferred to a pumping station and water treatment plant. Depending on the type of surface water, intake structures differ.

A suitable intake location is close to the bank of a river or lake at varying depths in the water body and in an area that is relatively free of silt, weeds, and grass to minimize clogging. Furthermore:

- The site should be near the treatment plant so the cost of conveying water to the facility is minimized.
- The site should not be near or immediately downstream of contamination sources.
- The intake must be located at a point from which water can be abstracted even during the driest period of the year, and which may permit greater withdrawals if required in the future.
- The intake site should be accessible at all times,

and the intake structure should be constructed such that it will be resilient to contamination and damage if flooding occurs. Moreover, sites prone to flooding should be avoided when siting surface water intakes.

An unprotected river intake consists of a submerged pipe placed on the bottom of a river channel. The outlet of the pipe is elevated from the bottom of the river and protected with a screen and a strainer to prevent sand, gravel, or fish from entering the pipes. Sand can irreversibly damage most pumps within seconds.

A protected river intake includes a number of screens designed to keep out floating material, such as trees and branches. The protected intake should be elevated at least 1 m above the riverbed to avoid boulders and rolling stones. The flow at the intake should be less than 0.1 m/s to create laminar flow conditions that reduce the drawing of silt and sediment into the intake. Inlets should always be submerged at least 0.3 m under the surface of the water to

avoid the formation of vortices that lead to the suction of air, which could affect the pump.

Floating intakes are used to abstract water near the surface to avoid silt loads that form at the bottom of some water sources. A flexible plastic pipe is connected to a float (pontoon), which can be constructed by attaching a steel or wooden frame to floats made from empty drums or plastic containers. Screens should be used to retain coarse material floating on the surface, which also might clog pipes and pumps.

Applicability and adequacy

River intakes should be located upstream from industries, densely populated and extensively used agriculture areas, sewer outlets and wastewater discharge points, as well as livestock watering places to reduce chemical and faecal contamination and/or silt. Intakes should also be located upstream of bridges to avoid the turbulence that may be created by water flowing past the bridge structure. The intake structures should be stable enough to remain intact even under flood conditions and should be designed to prevent clogging and scouring. In lakes, water should be collected at some distance from the shore to reduce contamination from human activity. In the upper layers of lakes, cyanobacterial (algal) scums might be present, and intakes should be designed to prevent these from entering the system. In these situations, the capacity to have variable abstraction heights permits the selection of a higher quality of water from the water column.

A protected intake can minimize the risks from fast-flowing river water that transports rolling stones or boulders, which can damage an unprotected intake structure. A river water intake always requires a sufficient depth of water. When the natural depth of the river is not sufficient or to cope with fluctuating water levels, a weir (a low, submerged, dam-like structure made of stone, concrete, or masonry) might be constructed downstream to ensure that enough water is available even in dry periods.

Operation and maintenance

Regular cleaning of screens and strainers is needed to avoid clogging surface water intakes. There should be a responsible caretaker who checks the intake structures routinely for damage and the accumulation of floating materials, as well as during and after critical events, such as floods or storms. During dry phases, periodic checks might be useful to ensure adequate water levels and adjust as needed, such as by building a weir.

Long periods of non-operation of the intake structures should be avoided to prevent the growth of mussels and vegetation on the screens. Backflushing the intake pipe may also be performed when it is clogged. If a small weir is used to elevate the water level

at the intake point, an accumulation of silt may occur behind the weir, making it periodically necessary to flush the accumulated sediments. Flexible pipes, used for example in floating intake structures, can be moved by storms, wind, or due to erosion and may need to be relocated after such events.

Fencing and other measures can provide special protection of the water intake sites, as intake locations are often remote, and animal access can also be deterred by such measures. Where possible, polluting activities should be restricted around the intake site (e.g. swimming, use of powered boats/crafts, keeping/watering livestock).

Health and environmental aspects/Acceptance

When a weir is built, the risk of flooding should be considered, since even small weirs can hold large volumes of water that can cause considerable damage downstream if the weir were to fail suddenly. Surface water quality is usually poor, and abstracted surface water generally requires multi-stage treatment before it is safe for consumption.

⊕ Advantages

- Usually simple and robust structures

⊖ Disadvantages

- Floods or human activity can damage intake structures
 - Clogging of screens and strainers can occur
 - Floating objects may collide with floating intakes
-

→ References and further reading materials can be found on page 208.

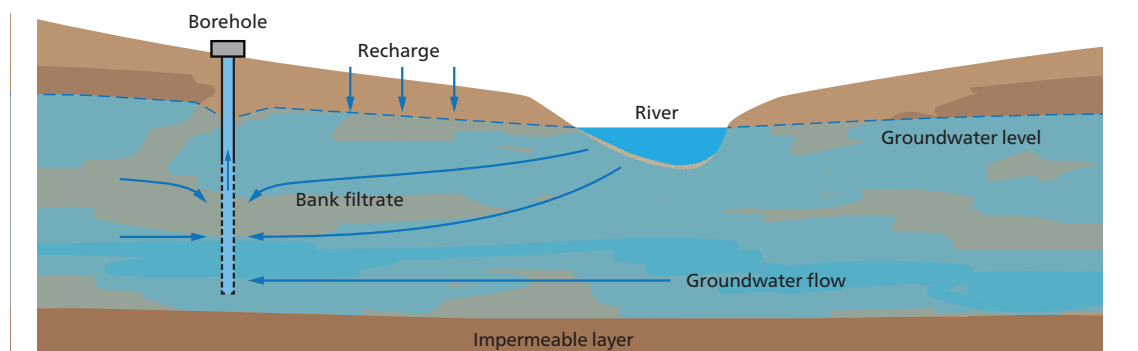
I.8 Riverbank filtration

Applicable to systems
2, 3, 4, 8

Management level
Community, centralized

Local availability of technology
or components
Mostly

Technology maturity level
Established technology



Riverbank filtration is a water abstraction technology that pumps water from boreholes that are typically drilled within a few hundred metres of the river bank. During the pumping process, surface water is forced to pass through the riverbed sediments. Through this filtration process, chemical and microbial contaminants are removed.

Most of the contaminant removal occurs in the zone between the river and riverbed sediments (colmation layer) due to the high microbial activity and small grain size of sediments in this zone. This zone thereby acts as a natural pre-filter that combines physical filtration, adsorption, absorption, and biodegradation processes. After these natural treatment processes, riverbank filtrate mixes with the groundwater present in the subsurface. As a result, water pumped from riverbank filtration wells is generally better quality than river water.

Riverbank filtration wells are designed vertically or horizontally. Vertical wells are commonly used for the extraction of smaller quantities of water and are typically located a few hundred metres from the surface water body. They extract water with long residence or travel times to ensure high contaminant removal efficiencies. Horizontal wells (collector wells) are used for

higher extraction rates and are located nearer the surface. The abstracted water has a shorter residence time and thus can still contain higher levels of some contaminants.

Although riverbank filtration can be effective in the removal of many contaminants, it should be used as a pretreatment process, and multi-stage treatment of the abstracted water is still required for safe consumption.

Applicability and adequacy

Riverbank filtration reduces the operation and maintenance efforts for raw water filtration and clarification, including reducing the demand for chemicals used in coagulation/flocculation processes as well as the frequency with which subsequent filters must be cleaned/backwashed when additional filtration steps are used. In some cases, riverbank filtration can completely replace other clarification processes. The water produced by this process is more biologically stable (has less organic material) than raw surface water. Riverbank filtration can further reduce fluctuations in water quality and temperature across seasons and weather events. Conversely, under certain conditions (reducing conditions), particulate iron and manganese can be solubilized in the subsurface, resulting in poor removal or even increased concentrations in abstracted

water, requiring additional treatment steps (such as oxidation/aeration and filtration) before the water can be disinfected and consumed.

Riverbank filtrate quality depends on many factors, including the composition and properties of the aquifer, river water quality, dilution with groundwater, the distance of wells to the river and filtration velocity, temperature, pumping rate, and the soil characteristics in the subsurface – particularly in the colmation layer. The efficiency of riverbank filtration is thus dependent on local conditions, which can make it difficult to define general procedures for site selection or general efficiencies for contamination removal.

Operation and maintenance

The level of water flowing from the riverbed and mixing with the groundwater should be constantly monitored to achieve sustainable water extraction.

Aquifer clogging is one of the major problems experienced with riverbank filtration. This can happen in poorly designed systems when suspended solids accumulate in the colmation layer and impede the percolation of river water into the subsurface.

Health and environmental aspects/Acceptance

River water quality is usually poor, and abstracted surface water generally requires multi-stage treatment before it is safe for consumption (see S.4 Rivers and streams)

The sustainable management of riverside groundwater resources is crucial to prevent groundwater exploitation and associated problems, such as saline intrusion, land subsidence, and deteriorating water quality. Details on sustainable groundwater extraction, including measurement techniques and methods for understanding the magnitude of groundwater depletion, can be found in the IUCN publication *Managing groundwater sustainably* (Smith et al., 2016).

⊕ Advantages

- Cost-efficient technology
- Robust natural treatment processes that produce water of better chemical and microbial quality, as well as better biological stability, than raw surface water

⊖ Disadvantages

- Risk of leaching or mobilization of aquifer contaminants
 - Applicability depends on local hydrogeology
 - Clogging of aquifer
-

→ References and further reading materials can be found on pages 208 and 209.

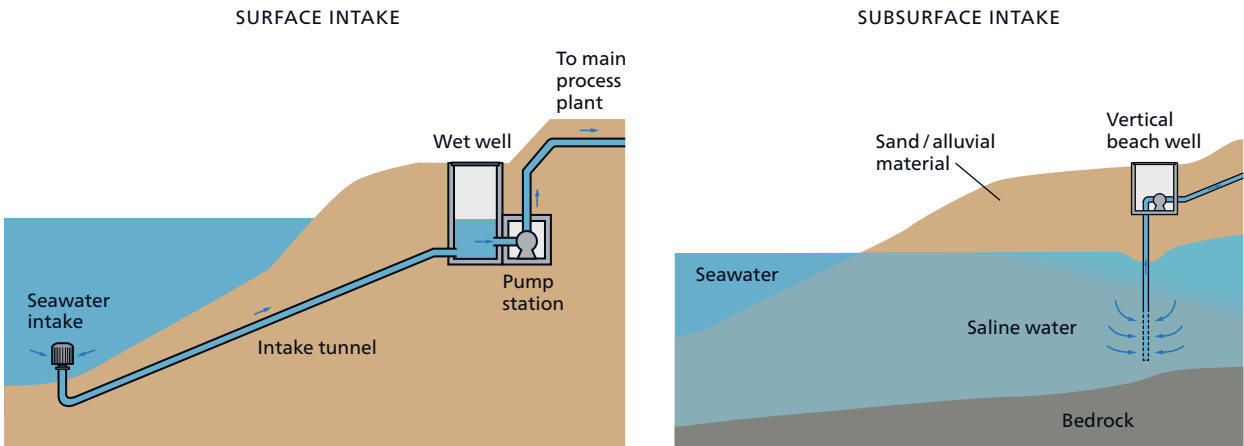
I.9 Seawater intake

Applicable to systems
9

Management level
Centralized

Local availability of technology
or components
Sometimes

Technology maturity level
Established technology



Seawater intake structures are designed to abstract seawater for desalination. Intake structures are categorized into surface and subsurface intakes that should abstract seawater without harming the marine environment.

The optimal location and design of infrastructures for seawater intake are very site-specific. The ocean is a dynamic water body that has powerful waves and changing currents that damage intake structures and alter the quality of abstracted water. Abstracted seawater quality affects treatment requirements, while the distance from the intake location to the plant has significant economic impacts. Desalination plants often use the existing intake structures put in place to provide the cooling water used in power plants.

Surface intake structures collect water above the sea bed and are mostly used by large desalination plants with capacities >20 000 m³/day. At the intake to the plant, seawater is pre-screened by traveling water screens, mechanical bar screens, and/or passive well screens. The screening chamber is often located on or near the shore, while the intake pipe can extend hundreds of metres into the ocean. Open surface intake structures can have a lifespan of 30–50 years.

Subsurface intake structures include beach wells, infiltration galleries, and other structures located

below the sea bed. Intake volumes from subsurface intake structures are generally lower compared to surface intake structures and are thus used in smaller desalination plants with capacities of around 4000 m³/day. The lifespan of beach wells is expected to be 15–20 years. Subsurface intakes naturally pre-treat seawater via a slow filtration through the sea bed. The collected water usually contains lower levels of solids, silt, oil, grease, natural organic contaminants, and aquatic organisms.

Applicability and adequacy

Desalination plants can impact the environment due to the need to discharge the concentrated brines produced in the desalination process (see System 9 Desalination of brackish and salt water) as well as due to the potential impact of intake structures on marine life. Organisms too large to pass through pre-screening filters and meshes (such as fish and crabs) can become trapped on these screens by the force of the flowing water (impingement) and can be injured or killed as a result. Smaller marine animals can pass through the intake screens and reach the treatment plant (entrainment), where they will likewise be killed by the treatment processes. Impingement and entrainment primarily occur with surface intake structures. Passive screens with slow-flowing water and thus little

force and/or additional measures such as fine mesh screens or fish buckets, can be implemented to prevent impingement and entrainment.

Subsurface intake structures, such as beach wells, need a minimum sustainable sea bed sediment layer through which natural filtration is accomplished. Beach erosion can remove the filtration layer over time, thus reducing the long-term well performance and lifespan of the intake structure. Therefore, locations where there is a potential for beach erosion in the vicinity of the intake wells should be avoided.

Operation and maintenance

The operation and maintenance requirements of desalination systems depend on the type of intake system. Surface intake screens need periodic cleaning with air to prevent solids from clogging the screen surface. The maintenance for subsurface intakes generally requires more effort (in terms of both finances and time). Yields from beach wells may diminish over time due to scaling of the well collectors caused by the precipitation of ions or bacterial growth. All well types require periodic cleaning, which can be achieved using weak acids, air or water surging, or sonic disaggregation and redevelopment. Infiltration galleries accumulate fine particles on the surface of the filter beds that impact intake capacity. The upper portions of the filter bed need to be periodically removed by dredging or replacing the upper portion of the filter bed media.

Health and environmental aspects/Acceptance

Subsurface intake designs can have potential negative impacts on nearby fresh groundwater aquifers. If the coastal aquifer from which seawater is drawn is hydraulically connected to a freshwater aquifer, the removal of large seawater volumes may lower the water levels and thus the production capacity of the connected freshwater aquifer.

Abstracted seawater is usually pre-treated (coagulation and filtration or membrane filtration) after intake to remove organic and particulate matter that will interfere with the desalination process (see T.5 Desalination). Further, a disinfectant is applied to reduce microbial pathogens in the treated water.

Subsurface structures:

⊕ Advantages

- Natural filtration of seawater, less pretreatment required
- No impingement and entrainment effects on marine organisms

⊖ Disadvantages

- Potential negative effects on nearby freshwater sources

→ References and further reading materials can be found on page 209.

Surface structures:

⊕ Advantages

- Provide larger volumes of water at lower cost
- Not dependent on coastal geology

⊖ Disadvantages

- Impingement and entrainment risks are high

Abstraction entails the capture and removal of raw water from a source and requires the availability of energy for subsequent transportation of the water to treatment plants, storage tanks, or distribution networks.

This chapter describes different abstraction methods, equipment that may be required, and associated energy sources that are commonly used.

Humans have used pumps for thousands of years. Over time, a wide variety of pump technologies have been introduced and evolved, though many of the ancient systems are still in demand today because of their distinct advantages in certain situations.

Major technological developments in pumping systems occurred around the time of the industrial revolution, and then again with the proliferation of cheap power from electricity grids. Even with these advances, the need for a reliable, high-quality water supply and the limited availability of electricity, engines, and fuel in some locations has necessitated the extensive implementation and development of manually operated pumps. Overall, a wide variety of pump types are commercially available - each developed to provide specific operational advantages.

Pumps are often categorized based on the method by which energy is added and the way in which the fluid moves through the pump. Three broad categories exist: impulse (A.1 Hydraulic ram pump), positive displacement (A.2 Piston/plunger suction pump–A.7 Rope and washer pump), and velocity pumps (A.8 Radial flow pump and A.9 Axial flow pump). Different sub-types are also described in this section.

A.1 Hydraulic ram pump

A.2 Piston/plunger suction pump

A.3 Direct action pump

A.4 Piston pump; deep well pump

A.5 Progressive cavity pump; helical rotor pump

A.6 Diaphragm pump

A.7 Rope and washer pump

A.8 Radial flow pump

A.9 Axial flow pump

Additionally, a range of energy sources available to drive the transportation of water from a source to a distribution network, treatment works, or storage facility is also discussed:

A.10 Gravity

A.11 Human powered

A.12 Wind

A.13 Solar

A.14 Electric

A.15 Internal combustion engine – diesel and petrol

The type of water source (e.g. surface water, groundwater, seawater), the quantity required, geographic considerations, and the availability of grid power or fuel all influence the decisions behind what type of pump and energy source should be employed.

For elevated water sources, such as an upland river or spring, the force of gravity can be used to transport the water through pipelines to storage tanks, treatment facilities, or directly to consumers.

For groundwater or surface water at elevations lower than the treatment works, storage facilities, or consumers, pumping is required.

Electricity and diesel are efficient traditional energy sources to abstract and convey raw water over long distances. When a local functioning electricity network is available, electric motors are preferable to internal combustion engines (diesel or petrol) because electric-powered pumps are easier to operate and maintain than engine-powered installations. Also, the high cost of fuel renders engines less favorable.

Alternatives such as solar, wind, and manual effort should also be considered, since they do not require any ongoing energy costs. Wind power is a good choice in locations where wind is constantly available throughout the year with average wind speeds greater than 2.5 m/s. However, when large quantities of water are required, wind power and manual effort might not be sufficient. Solar power can be an efficient alternative in remote areas with abundant sunshine, where fuel is expensive, or where grid electricity is not available. On one hand, it is important to note that solar- and wind-powered systems require a greater initial capital investment and more specialized technical skills

for maintenance compared to electric and diesel-powered pumps. On the other hand, they may be more cost effective over time, since there are fewer on-going costs and can therefore be paid back relatively quickly. Also, due to the inherently intermittent nature of energy availability with wind or solar, provisions usually need to be made for water storage.

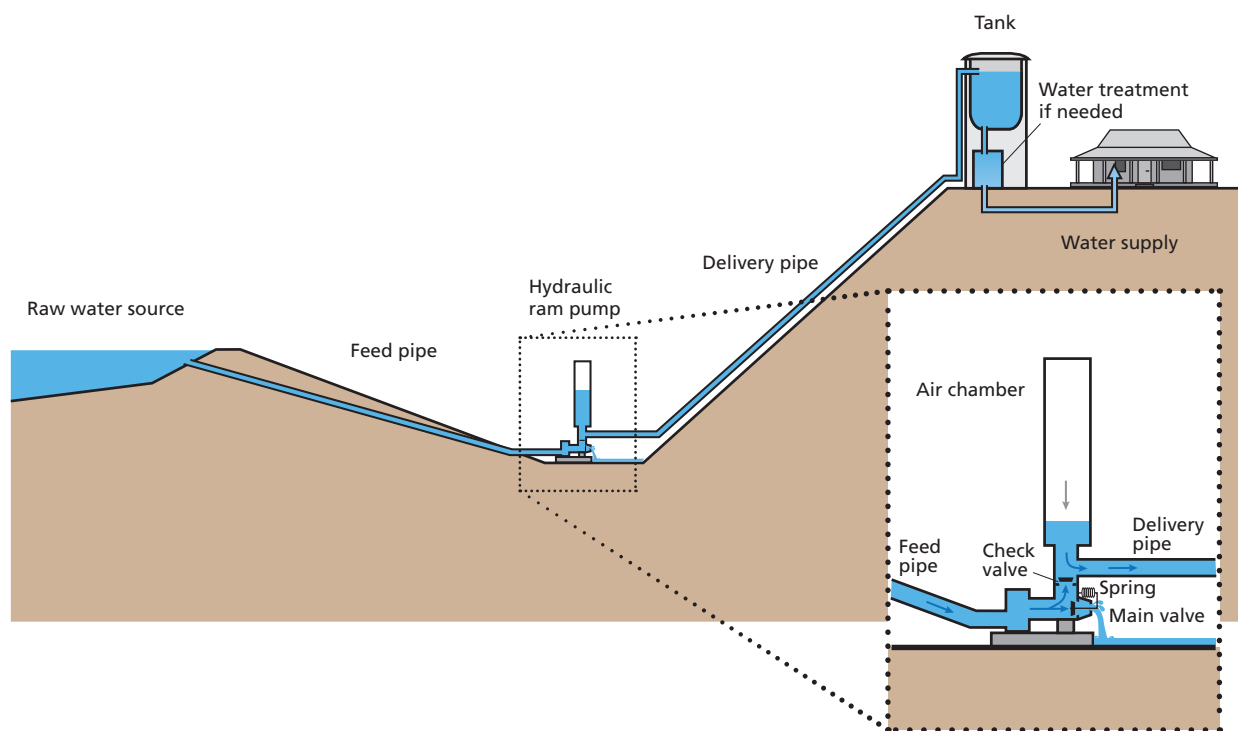
A.1 Hydraulic ram pump

Applicable to systems
3, 5, 6

Management level
Community with appropriate
technical support/
centralized

**Local availability of technology
or components**
Sometimes

Technology maturity level
Established technology



Impulse or hydraulic ram pumps are designed to reliably provide pressurized water from an existing source with little or no energy input. A hydraulic ram pump uses the velocity of an existing flow (e.g. a nearby river) and a difference in height to create a pressurized flow.

The pump, which is located at a lower level, uses a series of one-way valves and a compressible pocket of air to harness the energy (or impulse) of the flowing stream of water. The flowing water compresses the air pocket, which in turn forces a small amount of water through the pump discharge at a higher pressure, allowing water to be lifted to a level higher than the water source.

Hydraulic ram pumps can operate using only a difference in water level and pump location. Water can be pumped up to 40 times as high as the available height difference between the water and the pump installation, though only a small portion of the total amount of water entering the pump can be delivered to the outlet. The amount of water that can be delivered is governed by the ratio of the input and delivery

levels above the pump. Performance tables for ram pumps are usually provided when a unit is purchased.

Hydraulic ram pumps require a reliable source of water (drive water) and a site suitable for pump installation that is below the level of the water source. The minimum amount of drive water required is 0.12 to 0.17 L/sec for small pumps, and the minimum working fall (minimum height difference between the source and the pump) is 1 m.

Applicability and adequacy

Hydraulic ram pumps are mostly suitable for hilly or mountainous areas where the water source is situated lower than the desired point of use for communities. Usually streams, rivers, or springs can be used as a water source to operate a ram pump. Sufficient flow/capacity in the water source must be carefully considered, since much of the water volume delivered to the pump is used to power the pump and is returned back to the water source below the pump. In practice, only around 10% of the total volume available in the source is pumped to higher elevations.

Operation and maintenance

Hydraulic ram pumps can operate 24 hours a day, 7 days a week for many years with no external power and little maintenance as long as sufficient water is available to drive the operation. Hydraulic ram pumps have to be started manually by repeatedly opening the impulse valve until the pump continues to operate by itself. The weight or spring tension on the impulse valve has to be adjusted to achieve the correct frequency for automatic operation, which can be problematic when the delivery pipe is still empty. In most cases, some manipulation of the main valve will also be required during starting. The owner's manual will usually adequately describe the procedure for starting and stopping the pump.

Parts which may require periodic checking and maintenance include the main valve, check valve, and spring. Depending on the design and quality of the placement, even as often as once a year. It is recommended that the performance of the ram pump be checked on a monthly basis. Inlet filters on the feed pipe may require daily or weekly checks and cleaning, depending on the quality of the available water. If a feed well is part of the system (strongly recommended), floating particles should be removed weekly. The feed well will also require manual cleaning when sludge build-up approaches the level of the inlet of the feed pipe.

Since a water hammer puts considerable stress on the main housing, pipe system, and seals, care should be taken to fit the system exactly as recommended by the supplier. For proper performance and high efficiency, the feed pipe and the pump housing have to be rigid. Sturdy platforms for the ram pump improve the performance and ensure a long, trouble-free service life.

→ References and further reading materials can be found on page 209.

Health and environmental aspects/Acceptance

As the system runs on renewable energy, environmental impacts are negligible. There is also little possibility of injury to operators. Hydraulic ram pumps often pump from surface water sources, which are likely to be contaminated. Thus, the water requires treatment.

⊕ Advantages

- Requires no electricity or fuel
- Robust, due to few moving parts, and easy to maintain under local conditions

⊖ Disadvantages

- Requires natural elevation difference of 1 m or more between water source and pump position
- Has low output volumes (typically 1–3 L/sec)

A.2 Piston/plunger suction pump (Positive displacement pump)

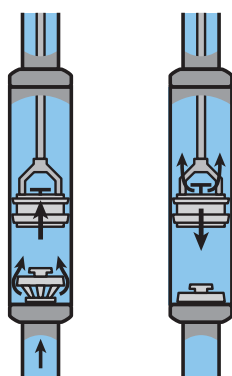
Applicable to systems
1, 3, 6, 7
(for water lifts up to 7 m)

Management level
Household/school/
neighborhood/community/
health center technical
support required

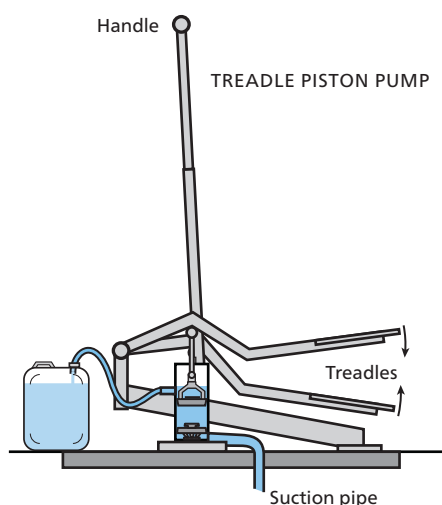
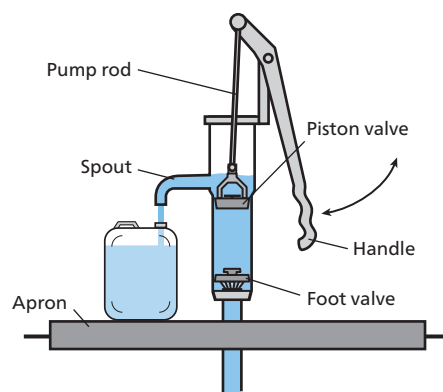
**Local availability of technology
or components**
Sometimes

Technology maturity level
Established technology

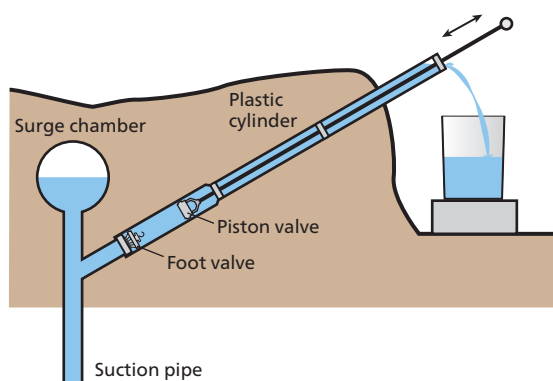
PISTON PUMP OPERATION



PISTON PUMP



ROWER PISTON PUMP



Piston/plunger suction pumps are a type of positive displacement pump, which displaces a fixed amount of water per cycle. Within this category, piston/plunger pumps are unique in that they function through a sliding seal within a cylinder, which is moved up and down (reciprocating action) to in turn force water through one of the two non-return valves – these are usually located within the pump head itself. This action creates a vacuum in the suction pipe, and atmospheric pressure on the water outside then pushes the water into the pipe.

Piston/plunger suction pumps are the only positive displacement pumps that usually have all of their

working parts above ground and where suction is used to lift the water. They can be both manually operated (by hand or foot) or mechanically-operated.

Once water is in the suction pipe of these pumps, there is a maximum height to which it can rise, which depends on atmospheric pressure. Theoretically, the maximum would occur when the weight of the atmospheric pressure pushing water up the pipe is equal to the weight of water in the pipe (i.e. 10.34 m). However, in reality, imperfect suction conditions and energy loss due to water movement in the pipe means that at sea level, this is more likely to be a maximum of around 7 m, and at higher altitudes, this will be even lower (e.g. to around 4.5 m at an altitude of 2400 m).

Suction pumps usually need to be primed to create a vacuum – this involves pouring water into the cylinder to create an airtight seal between the piston seals and cylinder. Having a non-return foot valve at the other end of the suction pipe helps to hold water in the pipe once it has entered. Leaking foot valves might require regular priming when the pump is emptied.

There are different varieties of this pump for both irrigation and drinking-water supply. Pumps meant for irrigation tend to be designed such that pumping occurs with the larger body parts that will not fatigue as quickly during prolonged pumping (such as the legs or back), and this results in a higher flow rate (between 3000–4500 L/h or 0.83–1.25 L/sec at 5 m depth) compared to non-suction types (2500–3000 L/h or 0.7–0.83 L/sec at the same depth).

Applicability and adequacy

Manually operated suction pumps can typically supply water to small communities of 50–100 people, although they also often exist at household level in different contexts. Mechanized suction pumps sometimes serve communities of up to 1000 people at rates of 25 L per capita per day.

Since this type of pump operates using suction lift, it is only suited for areas with a shallow water table. However, within this context, it can be useful in situations where an offset pump is needed (e.g. abstracting water from a riverbed well that is laterally offset below the river sand surface) or where the required water quantity is high (e.g. where water is used for productive use, such as irrigation).

Operation and maintenance

Piston/plunger suction pumps are relatively easy to maintain, since all of the moving parts are above ground level. In contrast to other pump types, piston/plunger suction pump maintenance can normally be done by a village caretaker or by the users themselves, requiring only simple tools, basic spare parts, and materials.

The basic skills needed for preventive maintenance (e.g. greasing, dismantling the pump stand, and replacing spare parts) can be quickly taught to pump caretakers. For major repairs, such as a broken riser pipe and cracks in the welding of metal parts, skilled technicians and specialized tools and materials would be required.

The parts that periodically require replacement are the valves and piston seals. Beyond this, little maintenance is required on the pump itself. This type of pump can have either plastic or metal for both the cylinder and suction pipe. Experience has shown that corrosion is more likely to occur where metal components are used in conjunction with groundwater with a less than pH 6.5, which in turn means more frequent replacement of affected parts – especially pump rods and pipes.

Health and environmental aspects/Acceptance

There can be health concerns with water quality with this type of pump, as the water source may be contaminated if dirty water is used for priming.

Chemical water quality has also been an issue in some metal pumps – when groundwater is less than pH 6.5, it becomes increasingly likely that iron from the pipes can dissolve into the water. The presence of lead is also a risk when it is used for the weighted non-return valve as part of soldering or from where it has been combined to make brass fittings – lead is found to leach out in water with both a low or neutral pH. In some cases, this means a direct health risk (for lead) or indirect health risk (for iron, which can cause or exacerbate the effect of iron-related bacteria that cause taste and colour problems to the point where people might choose a microbiologically unsafe but aesthetically more pleasing water source).

⊕ Advantages

- Has well-proven and robust design
- Has few moving parts, which are all above ground; therefore, low operation and maintenance
- Is simple to maintain under local conditions
- Is good for offset pumping situation

⊖ Disadvantages

- Has risk of contaminating the water source during priming
- Has maximum pumping lift of approximately 7 m at sea level (less at higher altitudes)

→ References and further reading materials can be found on pages 209.

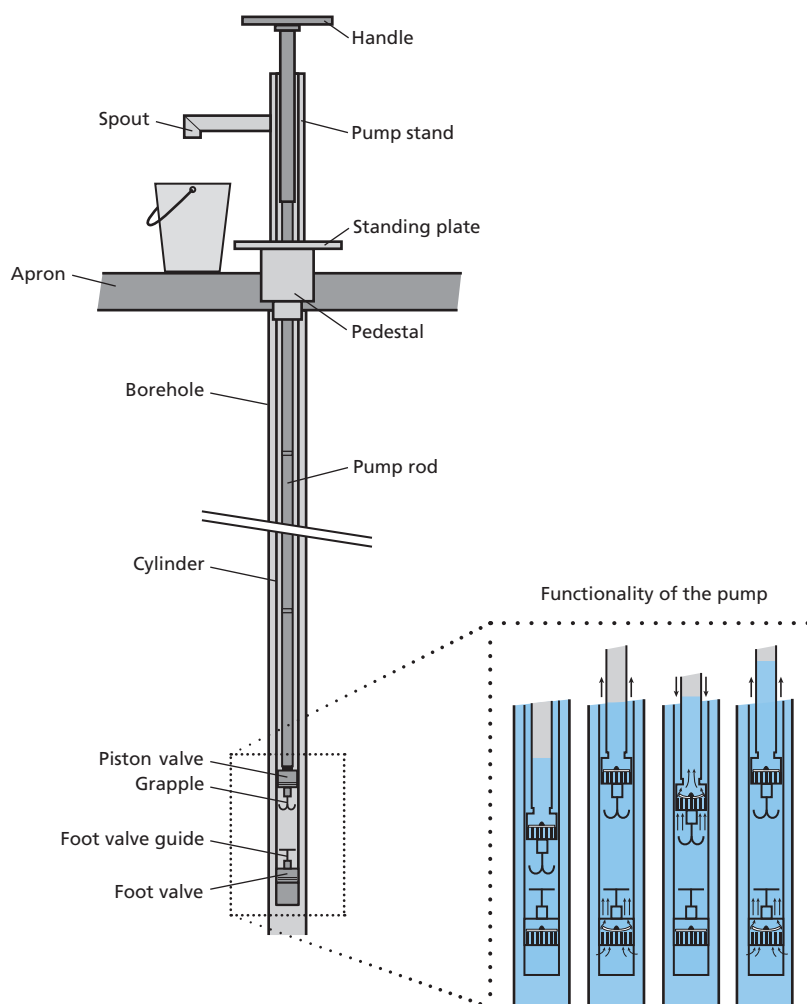
A.3 Direct action pump (Positive displacement pump)

Applicable to systems
1, 3, 6, 7
(for water lifts up to 15 m)

Management level
Household/school/
neighborhood/community/
health center; technical
support required

**Local availability of technology
or components**
Sometimes

Technology maturity level
Established technology



Direct action pumps are a type of positive displacement pump, which displaces a fixed amount of water per cycle. Within this category, direct action pumps are unique in that water is lifted or displaced directly by the user without additional levers or bearings (meaning maintenance requirements are less). Additionally, the below-ground components are mostly made from plastic, which makes them corrosion resistant and easier to handle.

Direct action pumps are operated by hand. They function through users lifting and displacing the water column directly in a reciprocating manner – this causes water to move into the pump head on both the upstroke and downstroke. This is made possible by two

non-return valves, one at the bottom of the outer pipe and the other at the bottom of the inner pipe. Two of the main types of this pump are the Tara and Canzee pumps, both using two non-return valves. However, the Tara uses an inner pipe that is hollow and sealed, which makes it buoyant. It also has a piston (with integrated non-return valve) that seals against the outer pipe such that the outer pipe acts as a cylinder. In contrast, the Canzee pump allows water to enter both the inner and outer pipes, and there is no piston or cylinder – rather water lubricates the two pipes. For the Tara pump, because the inner pipe is buoyant, less effort is needed on the upstroke and more on the downstroke, whereas with the Canzee pump it is the reverse. The installation of direct action pumps is simple and does not require lifting equipment or special tools.

Applicability and adequacy

Direct action pumps are installed on boreholes of limited depth (generally up to around 15m). Because the water column is lifted directly, pumping water from deeper depths is not feasible – the only way to do that is to reduce the weight of water in the pipes through modified pipe design. These pumps can abstract water at rates between 0.25–0.42 L/sec from depths of around 12m.

Direct action pumps are more cost effective than deep well hand pumps for medium lifts, and the configuration also provides protection against bacteriological contamination. They can be used as a “community” installation for up to 300 users.

Operation and maintenance

For the Tara pump, the buoyancy of the pump rod simplifies pumping operation. Any direct action pump can be easily operated by both adults and children if the water table is less than 5m below the surface. However, children may experience difficulty in operating the pump with depths of greater than 5m.

Operation and maintenance are easier for direct action pumps than deeper well pumps. This is because these pumps lift water directly using no levers or bearings, which are used by deeper well pumps – resulting in fewer pump maintenance issues in comparison. Also the use of plastic pipes and fittings means that extracting pipes is easier and more straightforward than for metal pipes – for the Tara pump, the foot valve can actually be removed without removing the outer pipe. Additionally, some of the parts can be manufactured locally (e.g. the valve washers for Canzee pumps can be made from inner tubes), which can improve sustainability. Another factor that reduces maintenance is the fact that pump rods and rising mains are made from plastic, making these pumps resistant to corrosion by groundwater with a low pH – this means less repair and replacement of components is needed.

This mechanical simplicity, low cost, and corrosion-resistant lightweight construction therefore makes it possible for a large part of the operation and maintenance to be carried out at the village level, and it usually only requires one or two people. Maintenance is relatively simple and can be quickly taught to users or caretakers.

Annually, the pump should be dismantled and checked. Small repairs that may be required include replacing worn seals, washers, and foot valve components, and replacing corroded lock nuts. Skilled personnel are required to carry out major repairs, such as repairing a broken pump rod or riser pipe or cracks in the welding of metal parts. Broken or damaged handles are also known to occur from time to time.

Health and environmental aspects/Acceptance

When correctly installed and maintained, direct action pumps do not pose any risk of microbial contamination of the water source. Additionally, there is little risk of injury while carrying out operation and maintenance tasks.

One issue with direct action pumps is the risk of over-exertion or injury, since water has to be lifted directly. For this reason, long pumping times are not suitable.

⊕ Advantages

- Operates where there is limited or no access to electricity or fuel
- Has well-proven and robust design
- Requires few moving parts, and those are easy to maintain under local conditions
- Provides relatively easy access to pipes and valves below ground
- Largely eliminates risk of water-source contamination and part corrosion by the material specification and the design of the pumps
- Is relatively cheap and easy to manufacture

⊖ Disadvantages

- Serves only small communities
- Is limited to 15m of operating lift
- Can be physically strenuous to operate, especially for children or the elderly

→ References and further reading materials can be found on page 210.

A.4 Piston pump; deep well pump (Positive displacement pump)

Applicable to systems

3, 4, 6, 7
(for water lifts of 2–30 m;
maximum 60 m under
practical considerations)

Management level

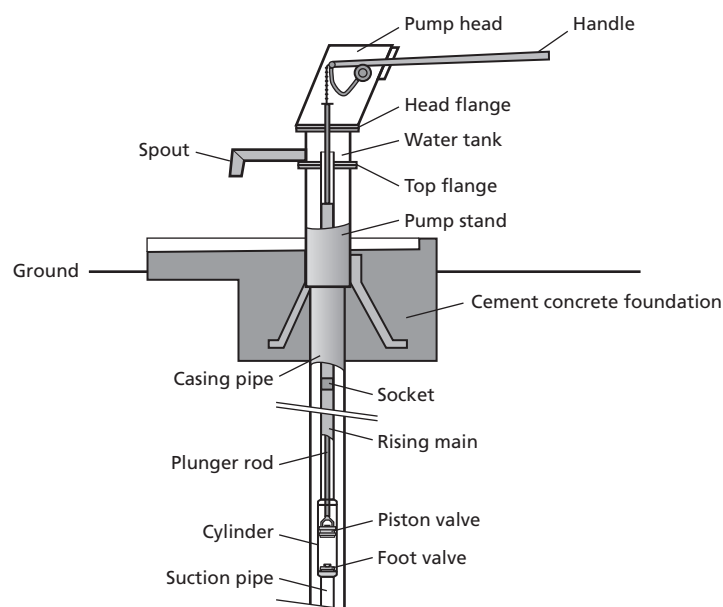
Household / school /
neighborhood / community /
health center; technical
support required

Local availability of technology or components

Local production is possible but
requires a good industrial base.

Technology maturity level

Established technology



Deep well piston pumps are a type of positive displacement pump, which displaces a fixed amount of water per cycle. Within this category, deep well piston pumps are unique in that water is lifted from deeper depths with the help of additional levers or gears.

Most deep well piston pumps are lever-action hand pumps, but flywheel action designs also exist. The pumping motion performed by the user at the pump stand is transferred to the piston by a lever and a series of connected pump rods inside the riser pipe.

Non-return valves within the cylinder ensure water is lifted in the rising main. The cylinder is usually 15–45 m below the ground, though up to 90 m is possible. These pumps typically yield 0.3 L/sec at lower lifts and 0.2 L/sec when installed at the full depth of 45 m. Deep well pumps can work at shallower depths, but some designs that rely on the weight of the pump rods for the downstroke (e.g. India Mark pumps) may not perform as well.

Riser pipes can be manufactured from galvanized iron or unplasticized PVC (uPVC). The connecting rods are usually plain mild steel, and the foot valves and plungers are usually brass or plastic.

Applicability and adequacy

Deep well piston pumps are manually operated pumps that are extensively used in many low-income countries in Asia and Africa. They are ideal for lifting water from boreholes or dug wells where the water table is beyond the reach of suction and direct action pumps and where the option of electrical or fuel-powered pumps is not viable. Several designs are approved and promoted by international organizations, and many have been installed since the 1980s.

Most deep well pump installations are too expensive for single-family use, so it is usually necessary that communal level installations be considered. In all likelihood, this will require investment by an external organization, such as a government department or a non-governmental organization (NGO).

Operation and maintenance

As the mechanism for moving the water is located below the water table, no priming is required. However, considerable effort is required to operate such pumps. Therefore, the pumps are usually operated by adults, and in some cases, two people operate them jointly. It is important that the pump stand and site be kept clean to avoid contaminating the water source.

Most pump cylinders now have an open top. This allows the piston and foot valve to be removed through the rising main for servicing and repairs, while the rising main and cylinder stay in place. In this case, the rising main has to have a large enough diameter to allow the piston and foot valve to pass, which can increase the pipe weight. This has been solved using plastic pipes for the rising main (e.g. India Mark 3 pump or Afridev) and by doubling up the casing to act as rising main at the same time (e.g. Blue Pump for a new borehole). In contrast, where cylinders are larger than the rising main (i.e. not open top, as with the India Mark 2 pump), removing a piston or foot valve requires removing the whole rising main pipe.

Pump rods have special connectors that allow them to be assembled or dismantled using simple tools. The connecting joints sometimes incorporate pump rod centralizers that prevent wear of the rising main.

Maintenance and repair can be carried out by skilled technicians. For preventative maintenance, usually only one or two people are needed, though this depends on the pump type. For example, older versions of such pumps often require specialized teams and lifting equipment for installation and removal. On the contrary, more modern versions usually do not require any special skills or equipment, and to a large extent, improved models of such pumps can be maintained largely at village level with only minimal technical support.

For common pump models, the availability of spare parts depends on the context – sometimes they are locally available, and sometimes not. The maintenance frequency can also depend simply on the quality of local pump parts, which might not be as good of a quality as elsewhere, even when the pump design has been standardized.

Daily maintenance activities consist of checking the pump performance and the quality of the water as well as tightening bolts that may have worked loose. Parts that might require periodic replacement are washers, plunger seals, and foot valve parts. Minor repairs may also include straightening bent pump rods and replacing corroded lock nuts. The pump should be dismantled and checked on an annual basis.

Due to the increased forces when pumping from greater depths, these pumps are prone to more technical failures. In certain settings, breakdowns can be expected every three to four months (e.g. for India Mark and Duba pumps) or monthly (e.g. for Afridev). The pump design can help them to function much longer between breakdowns (12–36 months for the Blue Pump). The most common technical challenges include failed plunger seals, hook-eye connectors, or lever handle bearings as well as the corrosion of metal components.

Skilled assistance will be required to carry out major repairs, such as attending to broken pump rods, riser pipe damage, or cracks in the welding of metal parts.

Health and environmental aspects/Acceptance

When correctly installed and maintained, the pumps do not pose any risk of introducing microbial contamination to the water source. One health issue is the possibility of over-exertion, even where the pumps provide mechanical assistance.

Chemical water quality can become an issue with some metal pumps – where groundwater is less than pH 6.5, it becomes increasingly likely that iron is dissolved into the water from the pipes. Lead can also leach out from certain welds and fittings regardless of pH (see A.2 Piston/plunger suction pump), both causing indirect health risks.

⊕ Advantages

- Has self-priming pumps
- Has a well-proven and robust design, suited to many users
- Mostly eliminates water-source contamination and part corrosion because of the material specification and the design of the pumps
- Can manually lift from deeper depths

⊖ Disadvantages

- Manually operated pumps can only serve small communities
- Is difficult and time consuming to operate hand pumps with a lift of more than 10 m
- Have more mechanical failures due to higher lifting forces
- Is more difficult to access the piston/valves on some designs
- Has greater operation and maintenance requirement than other hand pump types

→ References and further reading materials can be found on page 210.

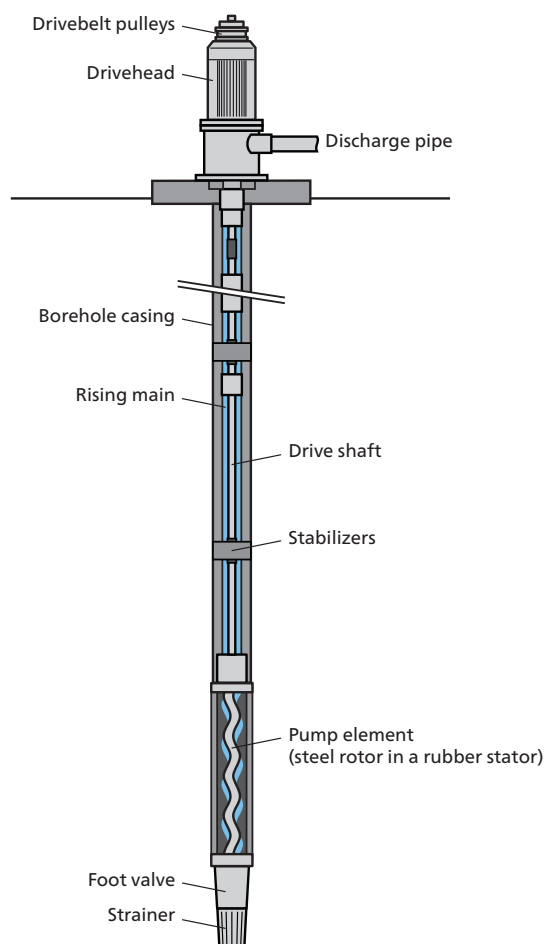
A.5 Progressive cavity pump; helical rotor pump (Positive displacement pump)

Applicable to systems
1, 3, 4, 6, 7, 8
(for water lifts of 2–300 m)

Management level
Community, technical
support required

Local availability of technology or components
Well-proven and robust motorized system used in suction pumps as well as in submersible pump systems; available from renown international pump suppliers

Technology maturity level
Established technology



Progressive cavity pumps are a type of positive displacement pump, which displaces a fixed amount of water per cycle. Within this category, progressive cavity pumps are unique in that water is lifted using a helical rotor rather than a reciprocating piston.

These pumps are extremely versatile and can be used in many different pumping applications. Most progressive cavity pumps are motor driven, although manually operated versions also exist. They are often also referred to as “mono pumps”.

Due to their design, helical rotor pumps are suitable for installation both above ground and in boreholes. Previously, the drive mechanism for a helical rotor pump was situated at ground level and connected to a drive shaft (either through a V-belt or a geared drive head), though now an electric motor is more commonly close-coupled to a short section of flexible drive shaft within

the borehole. The drive shaft is connected to the metal rotor that rotates, causing it to seal against the flexible rubber stator. This forms sealed cavities that move the water to the discharge of the pump. Fluid is moved at a steady rate that is determined by the rotation speed of the pump. This results in a fairly stable flow, regardless of the head (the pressure being pumped against, measured in metres) that must be overcome. This type of pump is capable of pumping to extremely high elevations.

Progressive cavity pumps can operate over a wide range of depths up to 300m with flow rates up to 50 000 L/h (13.8 L/sec) at low heads.

For the most part, the liquid being pumped acts as the lubricant between the rotor and stator. For this reason, “dry running” must be avoided, as this will result in rapid overheating and complete destruction of the polymer-based stator. These pumps should never be operated against a closed valve, since doing so can damage the pump and fittings. For suction pumps, there is a

maximum height to which water can rise in a pipe depending on atmospheric pressure, which itself varies with altitude (see A.2 Piston/plunger suction pump). Additionally, sufficient pressure needs to be available in the pipeline immediately before the water enters the pump. If this pressure is too low, it can result in a phenomenon known as cavitation, which causes rapid damage and failure of internal components. To prevent this, the net positive suction head (NPSH) needs to be calculated using atmospheric pressure at the pump site, NPSH data from the pump manufacturer, friction loss in the inlet pipe, and vapor pressure. Suppliers should therefore be consulted during project design to ensure that the pumps have the specified minimum pressure.

Applicability and adequacy

Helical rotor pumps are generally driven by electrical motors or internal combustion engines. They are known for high levels of mechanical efficiency, especially in smaller units. They are more suitable for pumping water with solids or abrasive particles compared to other common types of borehole pumps (e.g. velocity pumps), and are used for both drinking and non-drinking-water. However, borehole pumps still need to be sized and positioned correctly to prevent excessive velocity across a screen (which pulls more particles; see I.6 Protected borehole).

Operation and maintenance

For surface-mounted suction pumps, it is crucial to have a suction line from the water source that is completely free of air leaks, since the introduction of even small amounts of air into the suction pipe will result in a significant loss of pump performance.

Helical rotor pumps are not complicated, which makes them generally more reliable and easier to fix compared to other mechanized pumps. However, since they do consist of mechanical components rotating at a high speed, wear and tear is a reality that must be addressed. Previously, when the drive mechanism was at ground level and everything was easily accessible, maintenance was more straightforward, though issues did arise with the constant pump vibration causing shaft seal failures that needed to be repaired. Submersible pumps are now designed with close-coupled motors with flexible shafts that have no joints, meaning the lifetime of the parts is now five times greater than before. However, motor maintenance does require removing it from below ground.

Stators will wear out first, and for every two changes of stator, a rotor should also be changed. Stored stators degrade faster with increased heat, humidity, sunlight, or ozone, so they need to be stored correctly. If they are older than 5 years, there will already be some degradation and a decreased operational life when used.

Rotors are usually made of hardened alloy steel or stainless steel. However, where metal components con-

tact groundwater with less than pH 6.5 corrosion is more likely occur. This in turn means more frequent part replacement, so rotors are often coated with a chrome plating to provide resistance to corrosion and abrasion.

As with all motorized pump installations, suppliers usually recommend that both an active and standby unit be installed to ensure continuity of service when breakdowns occur that cannot be rapidly repaired.

Health and environmental aspects/Acceptance

When correctly installed and maintained, the pumps do not pose any risk of introducing microbial contamination to the water source.

Operators must be trained and made fully aware of the risk of injury associated with high-speed rotating equipment. Only trained personnel should be allowed to work on mechanized pumps. The area where the equipment is operating should be off limits to the general public, and there should be a way to shield people from fast-moving V-belts where these exist.

Chemical water quality can also become an issue with some metal pumps – where groundwater is less than pH 6.5 it becomes increasingly likely that iron is dissolved into the water from the pipes. Lead can also leach out from certain welds and fittings regardless of pH (see A.2 Piston/plunger suction pump), both causing indirect health risks.

⊕ Advantages

- Has well-proven design that is robust and manufactured by many reputable suppliers
- Flow rate does not vary too much with increasing head, so less design needed
- Is more resistant to aggressive groundwater (through having more stainless steel)
- Can cope with pumping solid particles

⊖ Disadvantages

- Requires trained service personnel for repairs
 - Must have precise alignment of installations for long service life
 - Can have costly and time-consuming repairs if the repair service is not available locally
 - Requires water inside the pump housing before starting; running dry for even a minute will destroy the stator
 - Has high starting torque that can result in starting difficulties and damage to stators
 - Not as readily available in certain settings
 - Running against a closed valve can damage pump and fittings
-

→ References and further reading materials can be found on page 210.

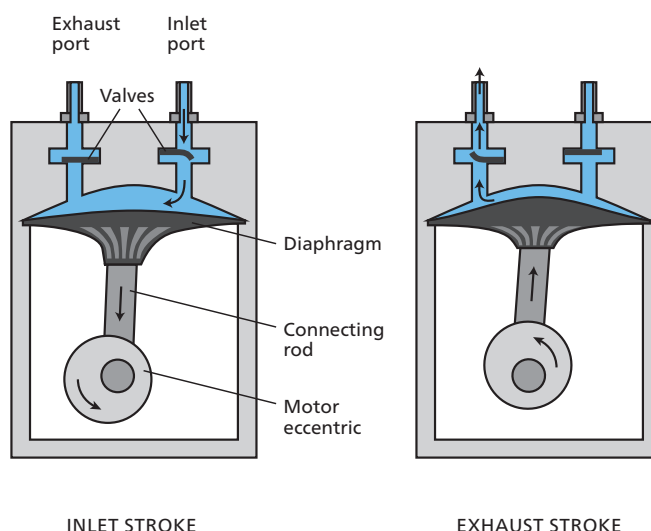
A.6 Diaphragm pump (Positive displacement pump)

Applicable to systems
3, 6, 7
(for water lifts of 2–60 m)

Management level
Community; technical
support required

**Local availability of technology
or components**
Available as submersible pump or surface pump in most countries; in some areas, manually operated versions are also available mainly for shallow water lifts

Technology maturity level
Established technology



Diaphragm pumps are a type of positive displacement pump, which displaces a fixed amount of water per cycle. Within this category, diaphragm pumps are unique in that they use a flexible diaphragm to force fluid through the pump.

Diaphragm pumps use a flexing diaphragm that moves fluid in and out of a chamber. During the suction movement of the diaphragm (inlet stroke), the outlet valve is closed, and fluid is drawn into the pumping chamber through the suction valve. When the diaphragm reverses direction (exhaust stroke), the suction valve closes, the pressure valve opens, and fluid in the pump chamber is pushed out through the pressure valve.

In community water supply applications, diaphragm pumps are used for various applications with flow rates ranging from around 0.2–0.5 L/second and pressure heads from around 15–100 m.

A wide range of diaphragm pumps is available to cater to these different applications. Solar-powered installations often use diaphragm pumps, since the mechanical efficiency is high and largely independent of the motor speed. Some suppliers also promote manually operated versions. These pumps can also be driven by motors and mechanical systems that convert

the rotating movement of motors into the required reciprocating motion action of the pump.

Applicability and adequacy

The principle of the pump is attractive because it allows thin flexible hoses to be used, making the pump easy to install or remove without the need for special tools or equipment. Different versions of diaphragm water pumps are designed for lifting or transporting water from almost any source to the point of use. They are particularly useful for small, controlled flow rates, for dosing chemicals and corrosive liquids (e.g. chlorine), or for pumping water with solid particles (e.g. when dewatering). As there are options that do not rely on electrical power, dewatering with diaphragm pumps can be achieved with compressed air if available.

The mechanical efficiency of diaphragm pumps is excellent. This makes the technology suitable for small pumps and for solar-powered applications.

Operation and maintenance

A diaphragm pump can be operated manually by pushing down on a foot pedal or sometimes with a handle. Pressing the pedal can take considerable effort, as much as the bodyweight of the user, and the pump must be built to withstand this.

Deep-well diaphragm pumps are typically installed to serve communities, so a caretaker should be appointed and trained to carry out the required day-to-day operation and maintenance tasks. The pump head, platform, and surroundings should be cleaned daily, and all nuts and bolts should be checked and tightened. The drive piston, rings, and guide bushing need to be checked monthly and replaced if necessary.

At least once a year (and more often if conditions warrant), components installed in boreholes should be checked, and the entire pump should be washed with clean water. In general, a pump can be extracted from the well by the caretaker and reinstalled within a few hours. Minimal tools are required to maintain the pump, though some system of technical support will be necessary to assist when major maintenance work is required.

Health and environmental aspects/Acceptance

When correctly installed and maintained, the pumps do not pose any risk of introducing microbial contamination to the water source. Risk of injury from high-speed rotating equipment must be considered if installations are motorized.

⊕ Advantages

- Has self-priming pump options
- Has well-proven and robust design and is manufactured by many reputable suppliers
- Easy to operate and perform minor maintenance

⊖ Disadvantages

- Requires trained service technicians for major repairs
 - Can have costly and time consuming repairs if the repair service is not available locally
 - May not be possible to operate by all users due to the physical effort required for manually-operated versions
-

→ References and further reading materials can be found on page 210.

A.7 Rope and washer pump (Positive displacement pump)

Applicable to systems

3, 4, 6, 7
(for water lifts of 2–30 m;
maximum 60 m under
practical considerations)

Management level

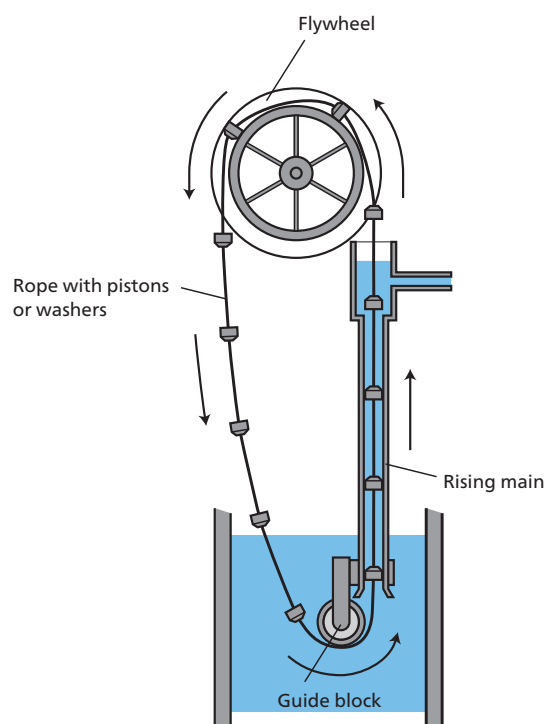
Community; technical
support required

Local availability of technology or components

Well-proven hand pump design
that can be locally built; drawings
are available from international
organizations

Technology maturity level

Established technology



Rope pumps are a type of positive displacement pump, which displaces a fixed amount of water per cycle. Within this category, rope pumps (also known as rope and washer pumps) are unique in that water is lifted directly using a continuous movement of a flywheel in only one direction (rather than in a reciprocating manner). The below-ground components are mostly made from plastic, which makes them corrosion resistant and easier to handle.

Rope pumps are usually manually operated, but can also be motorized. They function through a loose hanging rope that is lowered into a well. This rope connects a flywheel at the top with a flared entry point to the rising main at the bottom. The washers fit only loosely within the rising pipe, but this is enough to ensure that at a certain rotational speed of the flywheel, more water is lifted than falls by gravity around the washers. The net result is that water is drawn up through the pipe and flows into the pump head.

The rope pump can be produced with locally available materials and skills using small workshops. The metal flywheel is joined with sides of old tires, which help grip the rope and washers, and has two handles,

meaning it can be operated by either one or two people. A loop of polypropylene (PP) rope connects this above-ground flywheel with a guide below the water surface – nylon rope can be used, but it tends to slip and stretch more than PP rope. Washers are attached to the rope at intervals of 1 m and can be made from round disks made of rubber, such as from the side of old car tires – thousands of rope pumps in Latin America and Africa use this material. Alternatives consist of plastic pistons made of high-density polyethylene (HDPE), which are efficient and easy to standardize; leather or wood, which have been tried with less success; or knots matching the diameter of the pipe.

Manually operated rope pumps can be used for water depths of up to 50 m, while they have also been motorized for depths up to 100 m. Flow varies on the lift – manual pumps at 5 m depth can deliver around 5000 L/h (1.4 L/sec), reducing to 500 L/h (0.14 L/sec) at 50 m depth, while motorized pumps at 100 m depth can deliver 1100 L/h (0.31 L/sec).

The recommended riser pipe generally varies between 18 and 40 mm in diameter, depending on the required water lift (e.g. for lifts greater than 20 m, smaller pipes of typically around 25 mm are recommended).

Applicability and adequacy

The rope pump is best suited to household level or small communities with low numbers of users (e.g. up to 50), since the plastic materials are not as robust as other deep-well pumps. Manually operated rope pumps are used for drinking and productive purposes (e.g. small scale irrigation) in areas with water tables up to 50 m.

The installation of a rope pump is simple and does not require lifting equipment or special tools. The pumps are generally installed in dug wells, though there are also versions that fit into boreholes.

Operation and maintenance

The manual pump version is operated by turning a crank. As the mechanism for moving the water is located below the water table, no priming is needed. With lifts of 30 m or more, it may be necessary for two people to operate the pump jointly to lift the weight of the water in the pipe. It is important that the pump stand and site be kept clean to avoid contamination of the water source. Even though the typical model exposes sections of rope and pistons, when correctly installed on a sealed well, a rope pump delivers water of much better quality than traditional open wells.

Motorized rope pumps often deliver water into a tank, and consumers then collect water from a tap on the tank. In some cases, motorized pumps are equipped with a feature that allows manual pumping if required when the motor breaks down.

This type of pump is well suited for maintenance by semi-skilled technicians, as preventative maintenance requires only one or two people. All repairs can be done with few tools, and spare parts are usually easy to source. Operation and maintenance is easier than for other hand pumps, largely because of the simplicity of the design. There are fewer parts with no levers or bearings (apart from models with bearings on the flywheel axle), and as a result, there are fewer pump maintenance issues in comparison.

Daily activities consist of checking the pump performance and the quality of the water, as well as ensuring that the area around the pump is clean and that no foreign matter can enter the well. Greasing the bearings and checking the condition of other parts of the pump should be performed weekly. Parts that might require periodic replacements are washers, pistons, ropes, riser pipes, and support bearings on drive wheel.

Health and environmental aspects/Acceptance

For motorized systems, the sustainable use of the water source should be monitored carefully. Contamination of the water source can be avoided to a large extent if the openings of the well are kept small and the slab is kept clean and protected. This ensures that contaminated run-off water and wind-carried matter is guided away from the well opening.

However, there is a potential for microbiological contamination at the point where the rope becomes exposed within the pump head, but some designs mitigate this through a pump head cover – in any case, this risk is low.

+ Advantages

- Requires no priming
- Has well-proven and robust design
- Has lower operation and maintenance requirements than deep-well pumps due to fewer working parts, plastic components, and relatively easy access to the pipes and valves below ground
- Is inexpensive to install and maintain
- Can be manufactured locally

- Disadvantages

- Serves only small communities when manually operated
- Requires significant effort for manual operation of rope pumps with a lift of more than 5 m
- Has possible risk of contamination through touching the rope
- Has no foot valve, meaning each time pumping is started, the raising main needs to again be filled with water

→ References and further reading materials can be found on page 210.

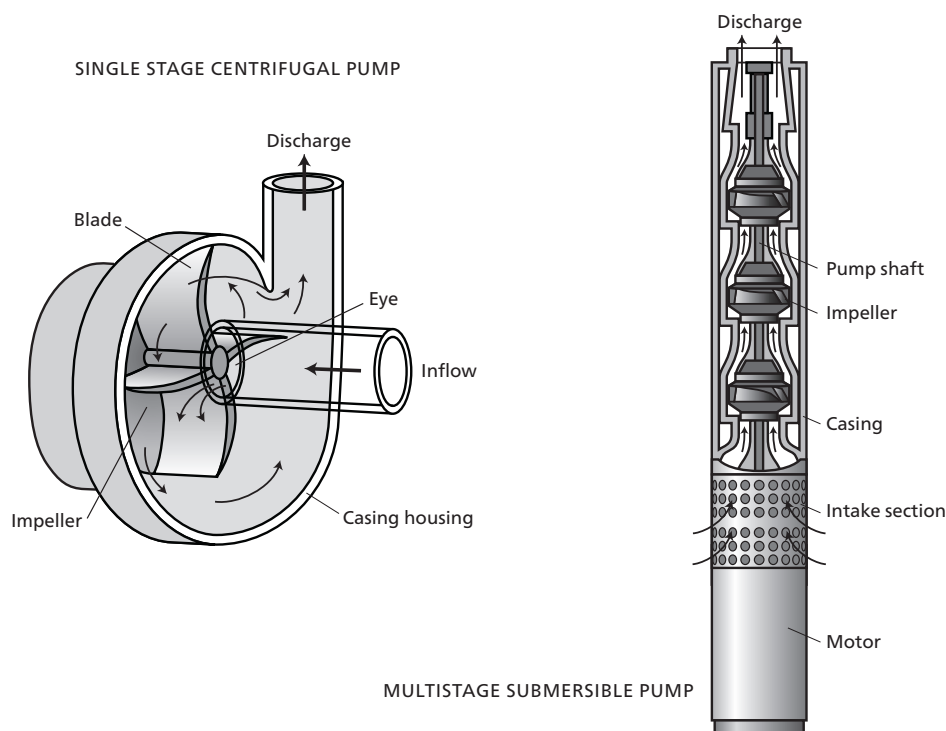
A.8 Radial flow pump (Centrifugal pump)

Applicable to systems
2, 3, 6, 7, 8, 9
(for water lifts of 10–600 m)

Management level
Community/centralized;
technical support required

Local availability of technology or components
Radial flow water pumps are produced in huge numbers worldwide by numerous of companies

Technology maturity level
Established technology



The most common technology used for pumping water is a velocity pump, which is one that increases flow velocity at the pump to convert kinetic energy into pressure energy. These pumps displace varying amounts of water depending on the rotational speed of an impeller that rotates on a drive shaft.

The main type of velocity pump is the radial flow pump (also known as centrifugal), unique in that it throws water outwards at right angles to the shaft. These pumps work through the motion of an impeller, which accelerates the flow of the fluid towards the outer edge of the impeller. This progressively increases the pressure while simultaneously creating a negative pressure zone at the inlet, which draws fluid into the pump. Pumps can be situated at ground level (suction pumps), but are otherwise submersible. They are generally driven by motors (electric or internal combustion).

The head, which is the pressure that is pumped against measured in m, of a single-stage centrifugal pump is largely governed by the type of impeller and the rotational speed. A series of several impellers (stages) can increase the pressure developed by a pump, and this is practical when either the rotational speed cannot be increased due to operating constraints or a larger impeller diameter would lead to

economical inefficiencies. Pumps can also be set up in parallel to increase the water quantity.

To achieve flow requirements, velocity pumps should be designed such that flow can vary significantly with differences in head. This requires creating a system curve based on the total elevation to which the water has to be moved including any additional energy (friction) losses in the pipe due to water movement at different theoretical speeds. Based on this, a pump is chosen such that the pump curve intersects the system curve at the desired flow rate. Pump operating points also need to be efficient – a pump that operates at an inefficient flow rate can develop multiple issues that can decrease pump life (e.g. wear and tear on seals and bearings or cavitation).

Borehole pumps situate the motor below the water intake, and motor cooling is achieved by ensuring a certain flow past the motor. Where this is not possible (e.g. below screens in a borehole or when the pump is used in a large-diameter well), then a shroud should be used to first direct water past the motor. Pump choice should also match the electricity supply on site (single or three-phase). When powered by solar, a variable-frequency drive (VFD) will be needed (see A.14 Electric).

For radial flow suction pumps, there is a maximum height to which water can rise in a pipe depending on atmospheric pressure, which itself varies with altitude.

Sufficient pressure also needs to be maintained at the suction port to prevent cavitation (see A.5 Progressive cavity pump; helical rotor pump). Standard radial flow pumps often have high velocities at the inlet and discharge ports (up to 10 m/sec). For suction pipes, maximum flow velocities should be approximately 1.5 m/sec, which limits the friction-generated pressure loss in the system. To achieve this, the pipeline diameter changes at the inlet and outlet of the pump. Low cone angles of 6–10° minimize the pressure loss when accelerating or decelerating the velocity and will protect the pump from possible cavitation damage while improving the overall system performance.

Applicability and adequacy

Radial flow pumps operate over a wide range of depths up to around 400 m, with flow rates up to 7 L/sec at lower heads. In general, they are good for higher flow requirements, since mechanical efficiency increases with higher flow rates (for flow rates between 3.3–33.3 L/sec, mechanical efficiencies between 70–80% are common). These types of pumps can be used for submersible as well as surface (dry) applications and are suitable for different water types depending on the actual pump design. For instance, some single-stage pumps are designed to pump solids, while multi-stage borehole pumps tend to have less space between the impeller and casing, and solids in this case can damage the pump.

Operation and maintenance

The motors of radial flow pumps can be configured to start and stop automatically based on various operating parameters, such as timers, pressure sensors, and flow requirements. Likewise, a range of protection measures can be installed to ensure that the pump and motor do not operate outside of their specified operating conditions.

For surface pumps, it is crucial to have a leak-free suction line to the pump inlet port. Any air in the suction line can considerably reduce performance.

Radial flow suction pumps installed at ground level are more straightforward to maintain, as everything is easily accessible. For submersible pumps, though, all the pipes have to be removed to repair or replace the pump itself. Repair and maintenance will be increasingly likely when pumps have not been sized correctly for the piped system (e.g. operating inefficiently) or are not sized or positioned correctly for a borehole (e.g. excessive velocity across a screen, which pulls in particles that degrade the pump; see I.6 Protected borehole).

Pump repair is carried out in a specialist workshop, so it is common to have both active and standby units installed in parallel. This setup can both increase supply under specific circumstances and ensure supply during time-consuming maintenance and repairs.

Metal is used for part of this type of pump, which means that when it is in contact with groundwater with less than pH 6.5, corrosion is more likely to occur. This in turn means the more frequent replacement of affected parts. In this pump, the galvanized iron riser main is more at risk than the other metal parts, which are made from stainless steel.

As with all motorized pump installations, suppliers usually recommend that both an active and standby unit be installed to ensure continuity of service when breakdowns occur that cannot be rapidly repaired.

Health and environmental aspects/Acceptance

Operators and maintenance personnel must be made aware of the risk of injury associated with high-speed rotating machinery. Electrical connections from pump to cable should be correctly spliced with waterproof resin to prevent electric shock or electrocution. This is especially important when pumps are used to dewater a structure where someone is present (e.g. a protected dug well during construction).

Chemical water quality can also become an issue with some metal pumps – where groundwater is less than pH 6.5, it becomes increasingly likely that iron is dissolved into the water from the pipes. Lead can also leach out from certain welds and fittings regardless of pH (see A.2 Piston/plunger suction pump), both causing indirect health risks.

+ Advantages

- Has well-proven and robust design and is manufactured by many reputable suppliers
- Is resistant to corrosion because it has more stainless steel
- Some types can pump solid particles
- Is readily available in most countries
- Does not need vertical borehole for installation
- Can be safely run against a closed valve for short periods of time

– Disadvantages

- Requires regular maintenance
- Is sensitive to operating conditions (flow rate changes significantly with increase in head, so a good pumping system design is needed) – poor conditions can significantly reduce the lifespan of pump seals and bearings
- Requires oversized power supply for startup current for electric motors
- Requires trained service personnel for repairs, which can be costly and time consuming if the repair service is not available locally

→ References and further reading materials can be found on page 211.

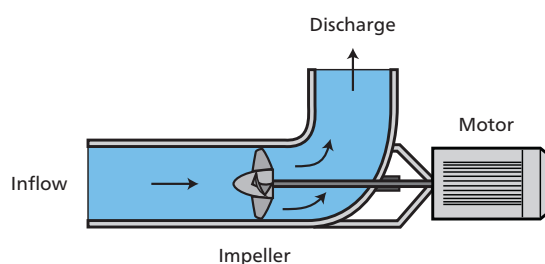
A.9 Axial flow pump (Centrifugal pump)

Applicable to systems
2, 8, 9
(for water lifts of 2–12 m;
maximum 15 m)

Management level
Centralized, technical
support required

**Local availability of technology
or components**
Widely available for low lifts in most
countries; produced by large
companies and small workshops

Technology maturity level
Established technology



Axial flow pumps are a type of velocity pump, which functions because increased flow velocity at the pump converts kinetic energy into pressure energy. Within this category, axial flow pumps are unique in that they transport fluid in the same direction as the drive shaft using the pressure difference at the impeller vanes (and not radially at right angles to the shaft, as with radial flow pumps; see A.8 Radial flow pump).

Axial flow pumps are suitable for large flow rates and low heads of up to approximately 15 m for a single-stage pump. The delivery characteristics of a pump can be changed by adjusting the blade pitch angle without new parts or machining existing ones. These impeller pitch blades can be variable or fixed – fixed pitch blades can only be adjusted by dismantling the impeller, whereas variable pitch blades can be adjusted during operation.

Propeller pumps are axial flow pumps. In water supply applications, they are often designed as tubular casing pumps. In tubular casing pumps, water passing the impeller and diffuser flows through a pump casing, which has a tube shape. When the column pipe is concentric with the pump shaft, the tubular casing pump is also called a vertical pump. Depending on the installation depth, successive column pipes are bolted together, leading to a long pump shaft. The pump shaft needs to be supported by several water-lubricated bearings, which are usually maintenance free and can handle turbid water. A sturdy axial bearing is required to absorb the axial thrust. The intake chambers must

be well designed, since the axial flow impellers are sensitive to disturbances in the approach flow.

Tubular flow pumps can be installed as dry-wet or wet-wet installations. In wet-wet installations, the pump is submerged in fluid, whereas in dry-wet installations, a booster pump is required to immerse the impeller continuously into fluid. Alternatively, a water- and air-tight intake elbow is used at the suction side to eliminate the need for a booster pump.

Axial flow pumps can be several metres or more in diameter and are usually designed as single-stage pumps. Multi-stage pumps are an option for higher heads, but they are usually so much more expensive that mixed-flow pumps are used instead.

Applicability and adequacy

Axial flow pumps can be used for drainage, land reclamation, irrigation, fluid mixing, or as a cooling water supply for power stations. For drinking-water supply, axial flow pumps are used mostly in pumping stations where large volumes of water need to be transported from dams and rivers to treatment plants, as well as in seawater desalination stations.

All axial flow pumps are driven by motors and generally use electric power or diesel engines. The optimum mechanical efficiency of such pumps can be as high as 90%. Since the efficiency peak is narrow, it is advisable to plan the system and pump carefully with the help of specialists. Most axial flow pumps have the power drive arranged outside the water flow. However, smaller submersible pumps are also available.

Axial flow pumps can only begin operating when the suction line is filled with water and the impeller is immersed in water. Therefore, pumps are mostly installed below the level of the water source. If the water level is below the impeller position, some priming arrangement is required.

Operation and maintenance

Axial flow pumps are often installed to deliver large volumes of water. Modern pump installations have sophisticated control and protection systems based on readings of power availability, pressures, flows, and timers. In low-income countries, small axial flow pumps are sometimes also produced in local workshops and used for irrigation, especially for flooding rice fields from ponds or from supply channels.

The tubular casing pumps (installed vertically) are designed to be pulled out so that the rotating assembly alone or with the diffuser can be easily removed and re-installed. This simplifies access for maintenance.

Axial flow pumps are simple machines, but they usually operate at high speeds and are driven by technologically sophisticated motors. The risk of injury from such high-speed machinery must be seriously considered. High-speed operation also implies that machinery can suddenly and rapidly fail, resulting in serious damage or injury. It is therefore important that operators and maintenance personnel are sufficiently skilled to ensure correct operating conditions.

It is necessary that adequate technical support be in place to support the operation and maintenance of axial flow pumps.

- Requires precise alignment of installations for long service life
- Is not possible to pump to high pressures
- Should not be used with a closed discharge valve
- Needs large depths of water in the suction pit to meet submergence requirements

→ References and further reading materials can be found on page 211.

Health and environmental aspects/Acceptance

As large amounts of water can be displaced with axial flow pumps in a short time, careful system planning in accordance with local environmental and legal framework is required to avoid negative effects on the environment.

⊕ Advantages

- Has well-proven and robust design and is manufactured by many reputable suppliers
- Can pump large flow rates
- Typically runs at low speed, so less wear

⊖ Disadvantages

- Requires regular maintenance
- Is sensitive to operating conditions, which can significantly reduce lifespan
- Requires oversized power supply for startup current for electric motors
- Requires trained service personnel for repairs and can be costly and time consuming if the repair service is not available locally

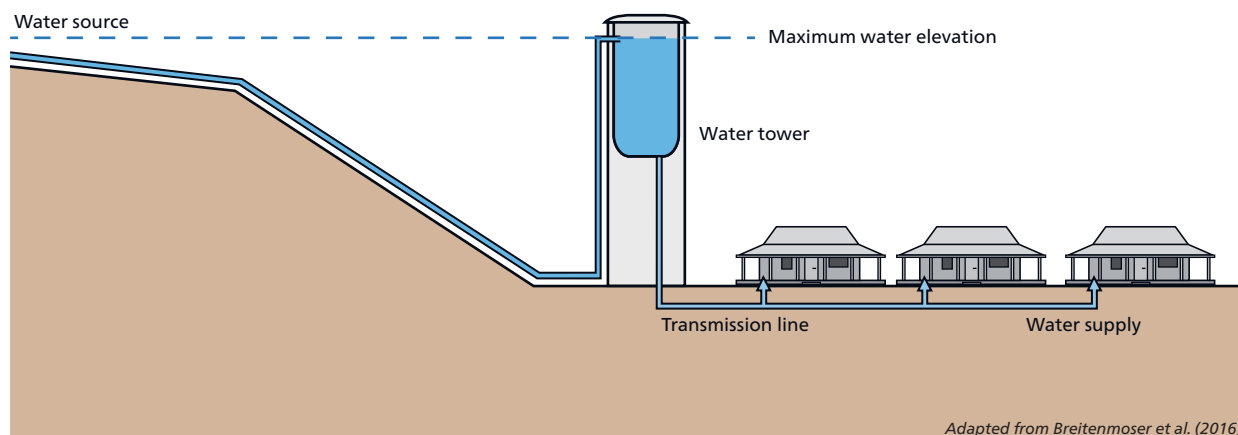
A.10 Gravity (Energy source)

Applicable to systems
1, 2, 3, 5, 6, 8

Management level
Community/centralized

Local availability of technology or components
Mostly (local availability sometimes problematic)

Technology maturity level
Established technology



Adapted from Breitenmoser et al. (2016)

Water transport is often most economical when the force of gravity is used to transport water through pipelines (or channels). As an energy source, the major advantage of using gravity as a driving force to move water is that it is economical (i.e. no power requirements) and pumps are rarely needed within a gravity system.

Gravity as an energy source can be used in many different stages in a water system. Water sources could be springs, streams, or simply an elevated tank from which gravity can efficiently deliver water to a treatment process and/or storage or from storage to supply points. The typical elements of a gravity-fed system include transmission pipelines, break pressure tanks, storage tanks, and distribution pipelines.

For larger systems, a topographical survey is essential for proper system design to ensure there is enough pressure at each point for sufficient water flow. The flow depends on the pressure state, energy loss due to water movement, and residual pressure.

The total energy of water at any specific point in a gravity system is the sum of its energy due to elevation, pressure, and velocity. When water is not flowing (e.g. in a full tank with closed taps), the pressure is related only to the difference between the level of the tap and surface of the water in the tank. This pressure, also called head, is measured in metres and is given as the energy per unit weight of water.

When a tap is opened and water flows, the actual pressure at the tap reduces because some energy is

lost due to heat transfer to the pipe, which then dissipates into the environment. This reduction of pressure energy is known as “friction loss” or “head loss”, and is a known quantity for each particular type of pipe when it is filled completely with water and open at the other end. This loss is typically stated as metres friction loss per 100m pipe. Friction loss varies according to the type of pipe and its diameter – for example, rougher or smaller pipes have more turbulence leading to more energy loss, so the pressure at the end of the pipe will be less. Also, the longer the pipe, the greater the friction loss.

With the known pressure loss, the pressure line (or hydraulic gradient line) can be calculated. Since some energy is lost when water is moving, the pressure will be less than when the taps are closed, so this line always slopes downhill from the source.

Importantly though, this line should always be above ground to keep air in solution (ideally 10 m or more, otherwise air-release valves should be used), and should never go underground, which causes negative pressure and a siphoning effect. This siphoning can introduce air into the solution and cause soil contamination via poor pipe joints, which could block the flow.

The hydraulic gradient line should also terminate above the last tap in the system so that there is an excess (“residual”) pressure at the furthest point. This ensures that water will flow at sufficient speed through the tap (considering some energy loss as well) while accounting for any discrepancies in actual pipe runs. The usual rule of thumb is to plan for at least 5 m of

residual pressure above taps. It is also possible to have too much pressure at a tap – when residual pressures exceed 56 m, measures have to be installed in the pipeline to reduce this pressure.

Applicability and adequacy

Due to long-term economic considerations and the simplicity of operation and maintenance, the possibility of installing gravity-fed systems should be thoroughly explored wherever there is the possibility of abstracting water from a high-lying source. It is particularly suitable in areas with higher topographical variation (e.g. hills, mountains) due to long-term economic considerations and the simplicity of operation and maintenance.

Operation and maintenance

The capital cost of gravity-fed schemes is generally higher than in schemes that obtain water from underground sources. This is due mainly to the costs associated with long pipelines from upland sources to lower lying settlements. The cost of dams, weirs, and captage structures can also be significant.

However, the running costs are usually low due to the absence of any need for electricity or fuel and the limited need for repairs, which are usually associated with electrical and mechanical equipment. Wherever possible, gravity-fed systems should be the preferred option. Careful consideration should be given to the overall life-cycle costs rather than simply using the initial capital outlays. In general, gravity-fed systems operate with much less risk of failure and associated supply interruption. For systems utilizing plastic pipes less than 250 mm in diameter, repairs can typically be implemented by locally without assistance from lifting equipment.

Maintenance requirements of the gravity-fed water supplies include cleaning screens at intake points and repairing pipe leaks and bursts. There is also sometimes a need to monitor pipe support systems, since pipelines are often installed over steep terrain and on rocky ground, which makes them susceptible to damage from a wash away or landslide.

Except in times of heavy rains, wherein the above-mentioned failures may occur, the supply from gravity-fed systems is highly reliable. Consequently, the level of service is usually very good.

Regular patrols of pipelines are required to identify necessary maintenance. This task can usually be accomplished by a single person, though implementing repairs may require a larger workforce to transport materials and undertake the actual work.

Health and environmental aspects/Acceptance

Failed pipelines can rapidly empty sources (reservoirs, tanks). Gravity is a well-accepted source of energy, as

the principle is easily understood by operators and the general population.

⊕ Advantages

- Has low total life-cycle costs
- Provides reliable supply due to not relying on fuel supplies or mechanical equipment (e.g. pumps) requiring repairs

⊖ Disadvantages

- May require high initial capital investment
 - Difficult terrain can make pipe-laying and repair difficult
 - Needs a natural difference in elevation for it to work, so not applicable everywhere
-

→ References and further reading materials can be found on page 211.

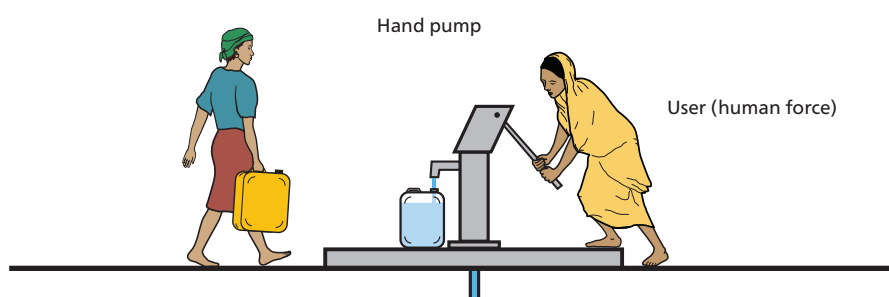
A.11 Human powered (Energy source)

Applicable to systems
4, 6, 7

Management level
Household/school/
neighborhood/community/
health center

**Local availability of technology
or components**
Mostly

Technology maturity level
Established technology



The most basic form of energy available for ensuring a household water supply is the effort that each person can apply.

To supply water for both drinking and irrigation purposes, human energy is commonly used to power water-lifting devices, such as pumps, as well as for transporting water from delivery points to individual households and treating the water at household level.

Many different variations of human-powered pump design have emerged over the millennia, with improvements that attempt to optimize the output from human effort and to enhance the reliability of the equipment. Significant advances to these pumps have been achieved over the past 50 years to meet the various demands for extracting water from underground water resources.

Protected wells and boreholes are by definition equipped with a pump and capped to reduce contamination. Where this is a manually operated pump, the design needs to allow water to be lifted using human energy alone. The typical criteria to be fulfilled is that it must be possible for only one person to operate the pump, though sometimes two is possible, such as with a rope pump. There are design parameters that enable this at different depths (e.g. smaller pipe diameter or levers for mechanical advantage) and flow rates (e.g. changing the body part used to pump with).

Where higher volumes of water are required, foot-operated pumps may be preferable. These pumps can produce water more easily using the legs, which

do not fatigue as quickly. Foot pumps tend to be used more for shallow depths up to around 6–7 m, depending on altitude, and are often suction pumps (see A.2 Piston/plunger suction pump). Beyond suction depth and up to around 15 m, the water column in the pipe can be lifted directly by the user using what are known as direct action pumps (e.g. Tara pump or Canzee pump; see A.3 Direct action pump). For depths greater than 15 and up to 45 m, mechanical levers are needed to make the work easier (e.g. India Mark pumps or Afridev; see A.4 Piston pump; deep well pump). Gearing mechanisms then allow water to be abstracted beyond 45 m in depth and up to 90 m (e.g. with a Duba Tropic pump), which is the limit for human-powered abstraction.

Applicability and adequacy

Human energy is most often used for water abstraction, transport, and treatment systems at a household or rural community scale where there is limited access to sources of energy and limited financial resources. In such cases, each family typically does the work to abstract enough for their own needs. Although human energy is a free power source, which can reduce ongoing financial costs, there are other costs that can increase at the same time, such as greater physical and time burdens for women and children.

Operation and maintenance

Day-to-day operation is carried out by individuals, usually to meet the requirements of their own household. Special arrangements may have to be made to

ensure that water is pumped and supplied to those that are in some way incapacitated (e.g. elderly and sick) and cannot operate the equipment.

The level of operation and maintenance needed will vary according to the type of human-powered system in use, and discussion of this topic often revolves around manually operated pumps. Despite the fact that the energy source is free, between a quarter and one-third of manually operated pumps are not functional nor in use due to various reasons, such as technical issues with the groundwater or borehole (e.g. corrosive groundwater or bad borehole design) or with the pump itself (e.g. quality of pump materials or pump age). There could also be many other reasons related to management, monitoring, finances, access to spare parts, or the skills needed for repair. This is a similar level of functionality to other types of water systems, but illustrates that a free energy source does not necessarily equate with better functionality.

→ References and further reading materials can be found on page 211.

Health and environmental aspects/Acceptance

The amount of continuous power output from a person is limited to around 70 Watts (50 Watts of effort is equivalent to lifting 0.5 L/s of water to a 10m elevation). It is therefore clear that the amount of water that can be moved or lifted through pumping by a single person is limited. Achieving this level of output also relies on the person being in good health and adequately nourished.

There is a possibility of injury from over exertion when pumping, especially when the pump is operated by children, the elderly, and people with other ailments or incapacities. Transporting water can also be physically hazardous, especially where paths are steep or slippery, and there are protection risks for women when the source is remote and insecure.

⊕ Advantages

- Free energy source, meaning lower ongoing financial costs
- Tends to be used with lower-technology infrastructure with a lower investment cost
- Low carbon option

⊖ Disadvantages

- Limited by amount of energy that people can produce, which limits the amount of water that can be abstracted or transported
- Cannot be operated by people with ailments or other incapacities
- Causes thermal stress in hot weather and other health risks, such as physical and protection hazards
- Contribute to gender inequality

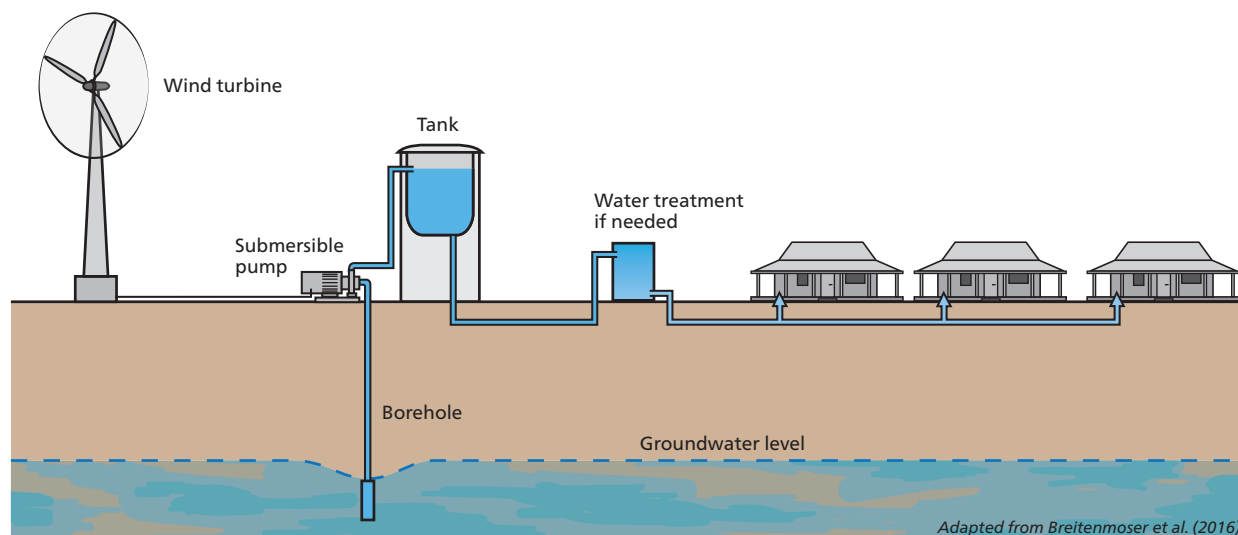
A.12 Wind (Energy source)

Applicable to systems
4, 6, 7

Management level
Household/school/
neighborhood/community/
health center

**Local availability of technology
or components**
Sometimes

Technology maturity level
Long established technology



Adapted from Breitenmoser et al. (2016)

Wind-powered energy systems use wind force either directly (e.g. to mechanically move a pump mechanism) or indirectly (e.g. to create electricity which can be used or stored).

Wind-powered pumps use the energy generated by wind to turn a turbine, often mounted on a tower, to lift water to a discharge point. In a wind-pump system, it is important to align the characteristics of the pump and the windmill. Mechanical wind-pump systems work by directly connecting a turbine to a mechanical pump system. The most common type of pump used for these systems is a positive displacement reciprocating piston pump. Such pumps tend to have a high starting torque requirement due to the need to overcome the weight of the pump rods and water already in the rising main. Once the rotor is turning, the torque requirement decreases due to the momentum that is developed. Windmills thus continue to operate even if the wind speed drops to 70% of the speed required to start the pump. A vane mounted behind the rotor ensures that the rotor continually faces the wind. However, this system is limited when the borehole is not in the best location in terms of wind speed and when the power characteristics of the turbine and this type of pump are mismatched, meaning power is not transferred efficiently at all wind speeds.

Electrical wind-pump systems, on the other hand, are more efficient, because standard three-phase

electric alternating current (AC) centrifugal pumps can be operated using power generated through a permanent magnet generator connected directly to the pump motor. Operation is possible since standard pumps are able to operate at variable speeds as long as voltage and frequency also vary, which is the case here. The advantages are that there is a more efficient match in power requirements (where the turbine and impellers in the pump have similar rates of increase in rotational speed) and that the pump can be offset away from the turbine – though this can cause a voltage drop in longer lengths of electric cabling. However, if the turbine receives higher wind speeds further away, the energy loss from the long cable lengths can be overcome by the extra power, such that the overall energy balance is favorable.

To provide for calm periods when the wind speeds are insufficient to operate the pump, storage for several days (typically at least 3 days) may be required. During peak wind conditions, the maximum flow should also be compatible with borehole design, with the velocity across the screens not exceeding 0.03 m/s and the drawdown still being sustainable (see 1.6 Protected borehole). To prevent damage from rotating too fast in high winds over 13 m/s, turbines should be equipped with an automatic reduction mechanism – this is done by furling the blades (where they are turned away from the wind). A manual override should also be included for positioning rotors and braking.

Wind energy is not only used for pumping water, but can also be used to generate electricity for other processes or fed to the grid. Energy can be stored using batteries (e.g. in hybrid systems that also use solar energy), though due to the cost, energy losses, and the short lifespan of batteries, it is generally better to avoid them. This can be done through a good design of the pumping system and adequate storage.

Applicability and adequacy

Wind-powered systems are usually appropriate for geographical locations with relatively constant wind speeds, and the exact wind requirements depend on the type of pump. For mechanical pumps that are optimized for low wind speeds (i.e. to pump water on most days), the minimum average speed required is 2.5 m/s. Typically, with a wind speed of 3 m/s, such pumps can deliver 0.12 L/s against a 10 m lift for each square metre (m²) of rotor area. Electric centrifugal pumps, on the other hand, require an average of at least 4 m/s.

To assess the suitability of a location for a wind-powered pumping system, it is essential that available wind data be thoroughly analysed. Such data are generally available in most countries and are often presented in the form of national wind resource maps, which are derived from measurements taken at meteorological stations. However, care should be taken with interpreting these maps, as they are often underestimated (due to under-maintained recording equipment at meteorological stations). In cases where there is no available data, empirical evidence and observations should be used, and local measurements should be taken over at least a full year.

The wind speed increases with height, so turbines are installed on towers. The exact height and site of the tower should be such that the turbine is not obstructed and is above the treetops, where it can properly capture the wind currents. In practice, this means placing it so that the rotor is at least 10 m above and 100 m from any surrounding trees and buildings. Therefore, an important consideration is whether the location has high and dense vegetation; in such cases, it may be difficult to use a wind-power solution.

Operation and maintenance

The useful life of a windmill is typically 20 years or more. Wind turbines can operate for long periods with little maintenance as long as the initial set-up ensures good lubrication of the gears and driving mechanisms, and the vanes and blades are protected against corrosion. All components should be inspected for corrosion damage. Bolts and general structural elements should be checked and tightened periodically. It is essential that gearbox lubrication is controlled and that the oil is topped up or changed as required. Turbine blades and/or bearings should also be checked frequently

and periodically replaced (typically after 10 years). To avoid potential damage, it is important that arrangements are made to apply the braking system during times of high wind speeds. Trained community members can carry out the routine maintenance, but larger scale repairs will require support from skilled and appropriately equipped technicians.

More operation and maintenance issues tend to occur around the pump itself, specifically the mechanical linkage between the turbine and pump, which tends to cause around 40% of all maintenance requirements. In addition, piston seals in the pump need replacing every one or two years. There can also be technical issues to do with the groundwater or borehole (e.g. corrosive groundwater or bad borehole design), which might increase the operation and maintenance burden.

Health and environmental aspects/Acceptance

Working on windmills can be hazardous. Tasks that must be carried out at the top of the tower present a significant fall hazard, and adequate precautions must be taken to safeguard against such injuries.

Injury can also occur if the moving parts of the structure are not adequately secured when work is undertaken. Large forces can be rapidly generated by gusts of wind, and serious injury may occur if workers are trapped between moving parts or parts that are dislodged from the tower when struck by part of the machine.

+ Advantages

- Requires no fuel or energy costs
- Uses renewable energy, a low-carbon energy option
- Is relatively low maintenance

– Disadvantages

- Requires large storage requirements to compensate for intermittent power supply
 - Locations must have year-round constant wind of 2.5 m/s
 - Has relatively expensive initial hardware costs
 - Requires specialist equipment and skilled technicians for major maintenance
-

→ References and further reading materials can be found on pages 211 and 212.

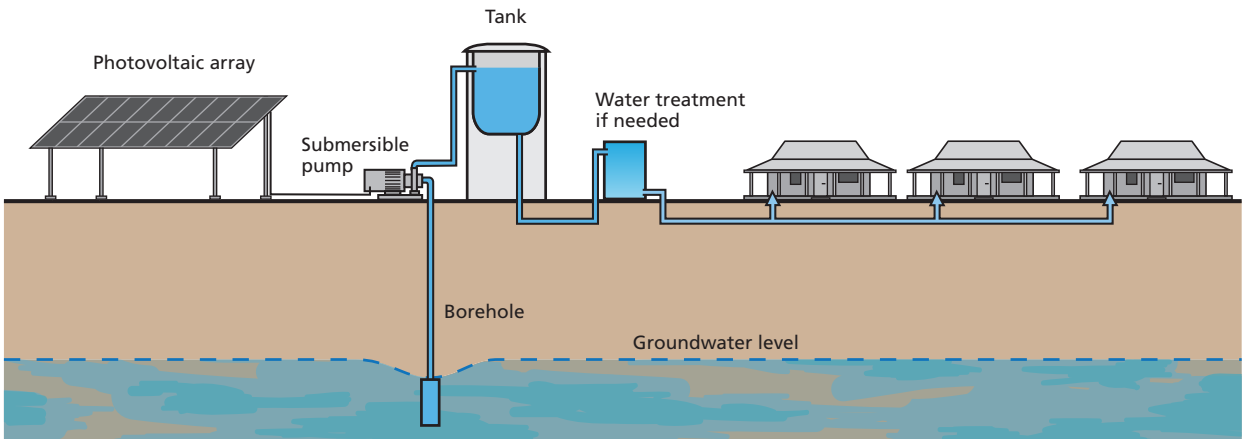
A.13 Solar (Energy source)

Applicable to systems
2, 3, 4, 6, 7, 8, 9

Management level
Household/school/
neighborhood/community/
health center

Local availability of technology
or components
Sometimes

Technology maturity level
Established technology,
rapidly developing



Solar or photovoltaic (PV) cells convert the radiation of the sun to electricity, which then powers a submersible or surface pump to abstract raw water.

Solar-powered pumping systems (SPPS) should be combined preferably with an elevated storage water tank (or, if unavoidable, with batteries) to ensure continuous water supply during cloudy days and after dark. PV cells are arranged together under protective glass plates, thereby forming a photovoltaic module. Solar modules are the basic elements that are commercially available, and when modules are connected to each other they form a PV array. The connection can be arranged either in parallel or a series to give different voltage and current outputs.

The number of modules that should be connected in the PV array depends on the amount of water to be supplied per day, the total dynamic head of the water scheme, the available solar energy (which varies daily, regionally, and seasonally), and the borehole characteristics (which might limit the possible peak flow due to the velocity across the screen). The average daily solar energy that can be used and hours of daylight are not identical, since solar intensity changes during the day. To be economically feasible for pumping, the daily average solar radiation at any site should be at least 3 kW/m² for every month of the year. Identifying the yearly and seasonal sunshine is therefore important to

decide whether solar panels are a feasible option for supplying power in a given area. The less hours available, the higher the investment costs, since a higher number of PV modules is needed.

Water storage tanks should be included in the water system for times when a pump is not running (e.g. during cloudy days and after dark) as well as to balance the daily fluctuations in demand. Usually, it is recommended that SPPS designs account for at least a 2-day supply of water storage. If sufficient water storage is not available, different power back-up options exist. For one of these options, excess electricity generated from solar panels can be stored in batteries, which are charged during the day and drained at night or during cloudy days. However, batteries reduce the efficiency of a SPPS and increase costs as well as maintenance and replacement requirements. Therefore, their use should be prevented if water storage is included. Alternatively, a second option for backup power includes making a hybrid SPPS by combining different energy sources (e.g. electric grid with solar or diesel generator with solar), to ensure pumping at night or on cloudy days, or as a backup power source for critical water schemes.

The electricity generated from PV systems is in the form of a direct current (DC). If it is required that alternating current (AC) motors be powered, inverters must be installed. In this case, standard inverters should be avoided in favor of a variable-frequency

drive (VFD), which will vary the necessary voltage and frequency (suited to smaller single-phase pumps without start capacitors, or any three-phase pump).

Applicability and adequacy

During cloudy weather, the electricity produced is significantly reduced (usually reduced to 25–40%). To maximize the direct sunlight radiation, the solar arrays should be securely mounted on a sun-facing tilted rack that faces the equator at a tilt angle equal to the latitude of the location and is placed in an area free of trees or nearby buildings. Solar panels should also be protected from strong winds, lightning, and falling objects, such as tree branches.

There are numerous software packages available that will facilitate the design process by computing all factors and geographical locations. They will also propose designs, including solar panel layouts, cable sizes, inverter or control box models, pumps, and assure the components are compatible.

Theoretically, any installation size is possible by simply connecting additional solar panel modules. SPPS are in principle able to pump water from 5–500 m in depth, and inverters are made for solar pumping applications to match pumps of over 210 kW. However, many pump manufacturers tend to specify pumps that are limited by other technical and practical considerations, such as recommending groundwater pumping up to 37 kW and pump lifts up to 150 m. In all cases, pumps should be specifically selected and matched to the solar power systems, and the suppliers of both the solar panels and the pumps should be consulted during the design and specification. Preferably, both aspects would be provided by a single supplier.

For SPPS systems, a wide range of both single and three-phase motor-pump combinations are available. Submersible pumps are most commonly used in deep wells due to their higher pumping head abilities, while surface pumps are used for shallow wells, lakes, or rivers. Diaphragm, reciprocating piston, radial flow, and progressive cavity pumps are all available as submersible solar-powered pumps from different manufacturers.

Operation and maintenance

Solar panel installations should function reliably for over 10 years without any major problems, requiring only minimal and simple maintenance in this time. Batteries (if used), inverters, and pumps, on the other hand, need more frequent servicing from skilled operators – hence periodic support from trained technicians should be available in the region to ensure sustainability.

The system should be inspected occasionally to check the pumping rate, condition of the PV panels, storage tanks, pipes, wiring, batteries, and control systems and to ensure that all electrical connections

are firm and protected from dust and water. Maintenance requirements include regularly removing the dust and dirt from the panels and protecting the panels from animal and human damage. To prevent theft or vandalism, different measures such as building a fence around the installation, welding the underside, and solar-powered lamps with motion sensors can be used.

Health and environmental aspects/Acceptance

SPPS are a well-accepted technology, since they offer an environmentally friendly energy source with low ongoing costs, and the operation and use are simple and reliable. SPPS are therefore gaining popularity as an alternative to manual or diesel-generator pumping.

However, there must be appropriate arrangements made for the disposal of old batteries if used. Care must also be taken when handling batteries to prevent injuries from potentially corrosive materials and exposure to a serious electric shock, which is possible in solar arrays of more than a few panels. Therefore, only knowledgeable technicians with adequate protective equipment should be allowed access when repairs need to be made. DC switches should be installed at critical points in the scheme to isolate different components and ensure electrical safety.

⊕ Advantages

- Are reliable, lasting, and robust systems with easy operation and maintenance
- Use a free, renewable energy source
- Is a modular system that can be closely matched to the required water supply
- Removes dependency on erratic or expensive fuel-chain supply
- Produces no pollution or noise

⊖ Disadvantages

- Requires high capital investment
 - Risk of theft of panels that are still seen as a valuable commodity in some locations
 - Specialist technicians and spare parts needed for repairs, which are often only available in large cities
 - Requires a certain minimum amount of solar radiation energy for successful operation (which varies regionally and seasonally)
 - Most applications need water storage capacity that is typically larger than for equivalent diesel systems
-

→ References and further reading materials can be found on page 212.

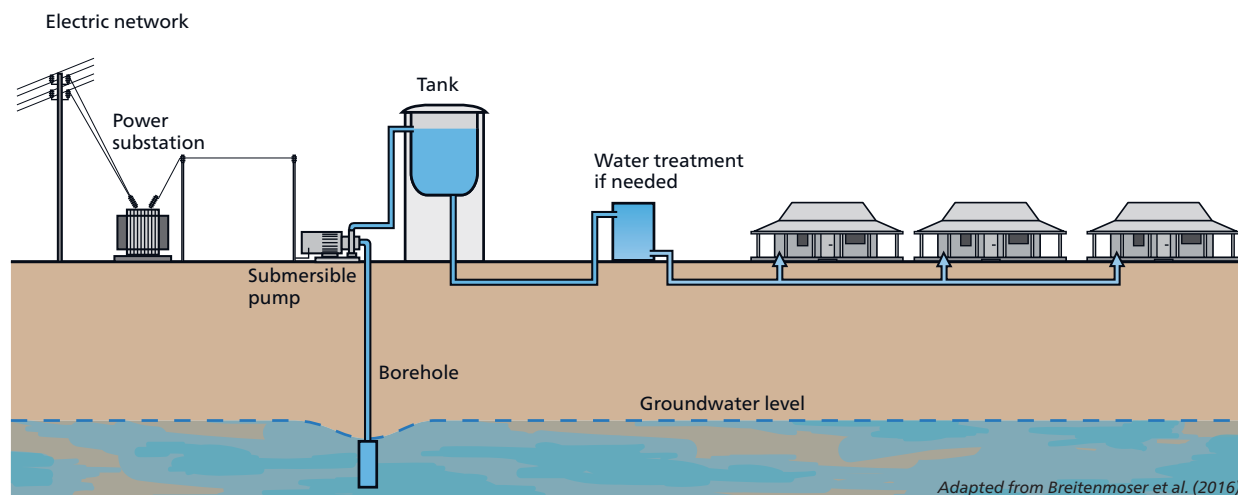
A.14 Electric (Energy source)

Applicable to systems
2, 3, 4, 6, 7, 8, 9

Management level
Community/centralized,
technical support required

**Local availability of technology
or components**
Not in all locations

Technology maturity level
Established technology



Electric-powered energy systems use electricity that has been generated somewhere and fed into a grid.

At the smallest scale, a set of solar panels or one diesel generator can produce the electricity needed to power a water system, such as a pump in a borehole. At a larger scale, the energy is produced further away by different means (hydro, solar, wind, or power plants based on diesel, coal, gas, or nuclear fuel, etc.) and put into transmission lines to users. In this case, the operation and maintenance are centralized, and power is fed into a grid that transports this energy over a distance for it to be used by multiple users.

Electricity is distributed to users through a network of power lines and transformers. Transmitting power over long distances is done at high voltages to minimize losses. Closer to consumers, transformers reduce the voltage to safe levels for industrial and domestic use. Depending on the location, power from a national grid is usually supplied at fixed voltages in either low single phase (110/220 V) or three-phase (208/400 V) arrangements.

To design water supply systems, key considerations include whether the supply requires direct current (DC) or alternating current (AC), and if AC, whether it is single phase or three-phase. All can be used for water systems, and the choice depends on the operating requirements of any piece of equipment. For example,

if a large pump motor is chosen with a noted motor voltage of 415 V, then a three-phase supply will be needed.

The electric motors used in these systems convert electrical energy into mechanical energy, usually in the form of a rotating shaft. This mechanical energy can then be used to operate various types of equipment and machines. Electric motors can be installed as separate units and connected to pumps and other equipment through V-belts, gearboxes, and shafts. Electric motors are suitable for high levels of automation, control, and protection since they can easily be switched on or off and adjusted through electrical signals received from sensors placed both on the motors themselves and on the machinery being operated.

Electrical energy can be stored using batteries, but in general it is better to try to avoid batteries through a well-designed pumping system and adequate storage – this is due to the cost and short lifespan of batteries and the inherent energy losses that occur during battery storage.

Applicability and adequacy

The use of electrical motors connected to a national grid is the preferred option for powering water supply machinery. The technology is well developed and has few limitations on the size of installation. Pump manufacturers produce small, low power consumption pumps as well as large, industrial-scale units.

In remote areas far from power-generating plants, however, there may be challenges associated with the adequacy of the grid for supporting the connected loads. This can result in voltage drops in the supply, and it can be extremely harmful to motors if they are operated at such low voltages. Suppliers usually specify that a voltage variation of only 10% should be allowed; it is usually recommended that motors be switched off during periods of low voltage. Motor control systems are often equipped with protection that will automatically stop the machine if voltage varies outside predetermined limits.

The need to install dedicated power lines over long distances can result in an excessive capital costs for installing electric motors and attached machinery. However, the cost of electricity is usually low when compared with the price of fuel, such as diesel or petrol. When making investment decisions, it must be considered that an initially high capital investment will be offset by long-term savings on fuel and maintenance costs, and that electric motors are probably the most reliable of drive systems for water supply machinery.

Operation and maintenance

Correctly designed and sized installations are extremely reliable and can operate for many years with few maintenance and repair requirements.

Routine maintenance checks do need to be carried out by skilled and authorized personnel, especially the inspection of all wires, cables, connections, and control panels, as well as checks of current, voltage, and frequency to warn of potential problems. Frequent checking for damage to insulation and the tightness of connections is essential. Lack of such attention can lead to machinery damage, fires, and even serious injury.

Where electricity is produced by a local generator, the maintenance burden and cost will increase significantly (see A.15 Internal combustion engine – diesel and petrol).

Health and environmental aspects/Acceptance

The danger of fire and injury to personnel must be seriously considered, and adequate protection and training must be implemented. Some simple safety rules can also reduce risks – if the work is far from a distribution board, then the supply should be disconnected at the isolator and the fuses should be removed. Wires should always be assumed to be live until tested, hands should be kept dry, fuses and circuit breakers should not be overridden, cables should be properly insulated and earthed, and it should be verified that everyone finished their work and is aware before switching the electricity back on. If battery systems are used, access should be restricted to avoid electrocution risks.

+ Advantages

- Is relatively low maintenance and therefore low overall cost to users when electricity is supplied through the grid – here maintenance is done further away in a centralized location
- Can be operated simply (but operators must be trained on risks)
- Automation is possible

– Disadvantages

- Produces medium noise
- Poses risk of fire and injury
- Can have high initial capital costs
- Requires specialized technical skills for maintenance and repair at centralized level
- May not be useful in certain contexts where power is unreliable

→ References and further reading materials can be found on page 212.

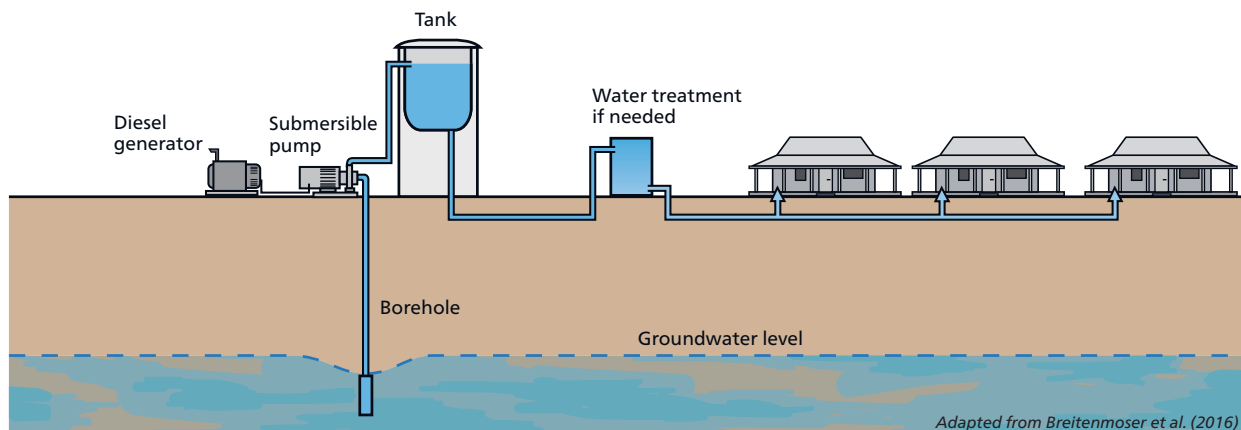
A.15 Internal combustion engine – diesel and petrol (Energy source)

Applicable to systems
2, 3, 4, 6, 7, 8, 9

Management level
Household/school/neighborhood/community/health center; technical support required

Local availability of technology or components
Sometimes

Technology maturity level
Established technology



Diesel and petrol (gasoline)-powered energy systems work by burning fuel directly on site to create the energy needed to power water pumping or treatment.

They can be used to drive pumps directly (normally with the use of belts or gearboxes), or they can indirectly produce electricity to power pumps. However, these systems have longer-term cumulative environmental and financial costs.

Commercially available internal combustion engines vary in size from around 2 kW to very large power ratings above 1000 kW. The number of cylinders can range from 1 to more than 16 in some cases. Typical engine speeds range from 750 to 2200 revolutions per minute. In modern engines, the operation cycle begins with air being compressed by a piston inside a cylinder into which fuel is injected by a high-pressure pump. The fuel is then ignited by the pressure in diesel engines or a spark plug in petrol versions. The rapid fuel burning and resulting gas expansion pushes the piston. The same movement of the piston is used to remove the burnt gases from the previous cycle. The linear motion of a piston is converted to circular motion through the crankshaft, which is used to drive pumps, generators, and other types of machinery. Diesel engines differ from petrol engines in that they do not have spark plugs to ignite the fuel mixture, and hence work at much higher pressures. Diesel

engines usually operate at lower speeds than petrol units, which results in less wear and tear. Engines typically have an operational lifespan of between 5000–50 000 hours (average 20 000 hours; diesel longer than petrol).

To supply water, diesel can be used as an energy source for both pumping and supplying energy for other treatment processes (e.g. dosing pumps). Key design considerations include whether the supply requires direct current (DC) or alternating current (AC) – for the former, a converter will be needed, and for the latter, it should be clear whether single-phase or three-phase is needed (see A.14 Electric)

Applicability and adequacy

The use of internal combustion engines is appropriate when electricity grid power sources are not available and relatively large volumes of water must be pumped (e.g. high yielding wells or surface water sources). Engines of all sizes are also often used as backup sources of power. It is important to select engines from reputable suppliers that can provide maintenance and repair services and reliably supply spare parts. When engines are used as the main source of power, an important consideration at the outset is how long the diesel-powered supply will be needed – given the current climate-change scenario, diesel should be designed out for medium to longer-term water supply applications whenever possible.

A diesel generator for water pumping should be sufficiently sized to run the pump, also with consideration for the additional power needed to start the pump. This involves understanding what total equipment will be drawing power from the generator now and in future. Additionally, the power output from diesel engines reduces with an increase in both temperature and altitude, which must be considered.

It is also important to consider how maintenance and repair might be undertaken. Large installations are not easily moved, and this may require technicians to carry out the work on-site rather than in workshops. This can contribute significantly to operation and maintenance costs and result in loss of service for long periods of time.

Operation and maintenance

Engines should be serviced (preventive maintenance) according to the number of hours run, as recommended by the manufacturer. For example, diesel engines require an oil and oil filter change every 250 hours (or half that if air temperature is more than 35 degrees Celsius), an air and fuel filter change every 500 hours (or more frequently depending on local dust conditions and if fuel is dirty), a major service every 1000 hours, and an overhaul every 10 000 hours.

While a generator should be large enough to start the motor, over-sizing should also be avoided since it can lead to excessive fuel and oil consumption. A load should be designed to be at least 40% of the rated generator capacity. Otherwise, running continuously on a light load risks clogging the injectors with carbon deposits of un-burnt fuel over time, which will then require a major service to decarbonize. Engines should also not be run at a speed exceeding 70–80% of rated capacity, as this will lead to premature wear and inefficiency. In general, water-cooled engines need less maintenance than air-cooled engines.

Internal combustion engines require an operator to be in attendance. Before starting the engine, the levels of fuel, oil, and cooling water (if not air cooled) should be checked and topped up if required. During operation, the caretaker should check the fuel level and oil pressure and ensure that the pump and generator are functioning properly. The readings from all gauges and metres should also be recorded.

The installation and operational costs for engine-powered systems are high, and operation and maintenance require a high level of technical skills. Troubleshooting problems based on symptoms requires experience. Poorly trained electricians tend to sometimes do a “fast fix” to get the generator working by bypassing safety switches, which can lead to more substantial damage later on. The reliable availability of fuel, lubricants, and spare parts is essential and must be planned. Regular maintenance must be im-

plemented, and technical support must be available. When diesel fuel is used directly from drums, it should be allowed to stand for twelve hours so that the sediments can settle to increase the life of the fuel filters and to protect the fuel injectors.

Health and environmental aspects/Acceptance

The use of internal combustion engines necessitates that water sources are adequately protected from contamination by fuel, lubricants, and fumes. If fuel is not stored and decanted correctly, it can contaminate groundwater—this risk can be minimized by storage on bunded concrete platforms.

The fumes and noise produced by engines can be hazardous to people working in close proximity to installations for extended periods. It is also important that caretakers are trained and made aware of the risks associated with high-speed machinery. The area where the equipment is operating should be off limits to the general public, and there should be a way to shield people from fast-moving V-belts when engine-driven pumps are used.

+ Advantages

- Can operate independently at remote sites where electrical power is unreliable
- Has possible high-power output

– Disadvantages

- Has high environmental cost
- Contaminated fuel can cause serious damage
- Produces noise and particulate pollution, as well as pollution risk to soil and water.
- Depends on regular fuel supply
- Is expensive to operate and maintain
- Is difficult to automate
- Requires skilled technicians

→ References and further reading materials can be found on pages 212 and 213.

This section describes water treatment technologies that are generally appropriate for larger groups of users. It includes community treatment options, semi-centralized applications in neighborhoods, and centralized-type applications in urban areas. Household water treatment methods are described in section H.

All water treatment methods can be divided into five groups (T.1–T.5 below) that can each function as a single-step treatment or could be applied as part of a large, multi-stage treatment. The five groups are structured around the type of contaminants primarily removed by the method, though some treatment technologies can be applied to multiple contaminants from different groups. See Annex 2 for a summary of technological interventions at the treatment level.

T.1 Clarification

T.1.1 Roughing filtration

T.1.2 Rapid sand filtration

T.1.3 Microfiltration

T.1.4 Coagulation/flocculation/sedimentation

T.1.5 Coagulation/flocculation/filtration

T.2 Removal/inactivation of microorganisms

T.2.1 Chlorination

T.2.2 On-site electrochlorination

T.2.3 Ultraviolet (UV) light disinfection

T.2.4 Slow sand filtration

T.2.5 Ultrafiltration

T.2.6 Pasteurization

T.3 Treatments for geogenic contaminants

T.3.1 Fluoride removal methods

T.3.2 Arsenic removal methods

T.4 Treatments for organic and inorganic contaminants

T.4.1 Activated carbon

T.4.2 Ozonation

T.4.3 Nanofiltration

T.5 Desalination

T.5.1 Membrane distillation

T.5.2 Reverse osmosis

As illustrated in Part 1, a meaningful combination of technologies is necessary to achieve safe drinking-water. Context-specific factors should be considered when choosing a treatment method or combination of methods, including (see also Annex 2):

- Availability of the water resource and its seasonal variations
- Water contaminants and seasonal variations in contamination
- Legal water quality and quantity requirements
- The application of multiple barriers, so that the failure of one barrier may be compensated by the effective operation of the remaining barriers
- Scale
- Availability of financial resources
- Local availability of materials or need for imported products
- Space availability
- Availability of skills and local capacity for design, management, operation and safety
- Sources of energy

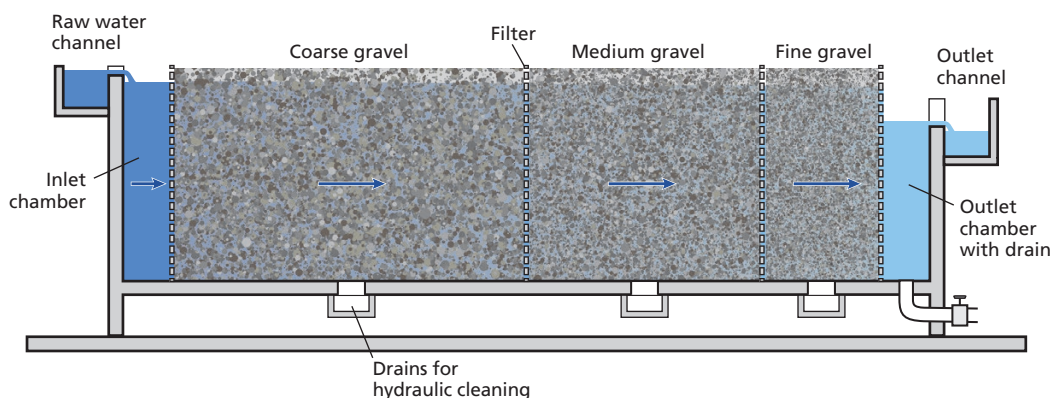
T.1.1 Roughing filtration

Applicable to systems
2, 3

Management level
Community, centralized

Local availability of technology
or components
Yes

Technology maturity level
Established technology



Roughing filters are used to remove suspended solids from turbid water (typically up to 100 nephelometric turbidity units [NTU]) through the sedimentation of particles on a gradient of filtration media ranging from coarse gravel to sand. Roughing filters are typically used as pretreatment processes to remove suspended solids that could rapidly clog a downstream filtration step (e.g. slow sand filter). These filters ultimately improve the disinfection efficiency and aesthetic quality of water in combination with downstream treatment.

Roughing filters typically use a gradient of filter media ranging in size from approximately 24 to 4 mm, decreasing in the direction of water flow (see figure above). This use of different grades of filter media, decreasing successively in size, supports the penetration of particles into the filter bed. It also combines the advantages of the greater storage capacity of the larger media with the higher removal efficiency of the smaller media. Ideally, the filter media fractions should be as uniform as possible to increase filter pore space.

The filtration media may consist of gravel from a riverbed, broken stones or rocks, burnt clay bricks, plastic material such as chips that are typically used for trickling filters, burnt charcoal, or coconut fibers. Roughing

filters are operated at small filtration velocities, on the order of 0.3–1.5 m/hour. At increased filtration rates (2 m/hour), particles penetrate deeper into the filter bed, which decreases the filter efficiency.

Roughing filters can flow in different directions. In addition to the horizontal flow pictured above, these filters can also be vertical. Vertical (downflow or upflow) filters are classified according to the manner in which the layers are installed. The differing fractions of gravel are filled in separate compartments and form a filter “in series” or are placed on top of each other to form a filter “in layers”. Intake and dynamic flow roughing filters can be included as part of an intake structure or installed at a water treatment plant.

Applicability and adequacy

Roughing filtration is applicable where there is a high concentration of suspended solids in the source water (up to 100 NTU) that needs to be removed before downstream filtration steps (e.g. slow sand filtration). This process ultimately improves the efficiency of disinfection and the aesthetic quality of the water.

Although designed primarily for the removal of suspended solids, colloids and certain classes of pathogens may also be removed to a lesser degree in roughing filters. The removal efficiency for these compounds depends on the configuration and design parameters

of the filter, though it is generally lower compared to rapid sand filters. The efficiency can be increased in roughing filters with a smaller filter media size at the last layer and slow laminar flow conditions.

Roughing filters were originally developed for community water supplies due to their lower operational costs and requirements compared to conventional coagulation/sedimentation methods. This makes these filters applicable in situations with limited local capacity and financial resources for operational expenditures or where reliable supply chains for consumable chemicals are not available. However, capital expenses exceed the costs of the coagulation process (see T.1.4 Coagulation/flocculation/sedimentation and T.1.5 Coagulation/flocculation/filtration).

Operation and maintenance

In upflow roughing filters, solids penetrate deep into the filter medium, and therefore hydraulic filter cleaning is needed. This can be done by lowering the water table in the filter to wash down loosely accumulated aggregated solids. High filter drainage rates and adequate installations enhance the cleaning by drainage. To reduce the amount of treated water used for washing, the valves connected to the underdrain system of the filter should be opened and closed quickly. In horizontal-flow roughing filters, it is important to start cleaning at the inlet side where most of the solids are retained. High levels of organic matter in raw water require a high frequency of hydraulic cleaning to reduce filter compaction and clogging, which require manual cleaning. Roughing filters should be more thoroughly cleaned manually after about 1 year of operation, depending on the turbidity of the raw water, by excavating the filter material from the filter compartment, washing it separately, and refilling it into the compartment. Besides hydraulic and manual cleaning, additional regular maintenance activities include repairing fissures, applying anti-corrosive agents to metal parts (valves, rods, and pipes), checking and lubricating the different valves, skimming off floating material from the free water table, washing out coarse settled material, and replacing defective parts.

Health and environmental aspects/Acceptance

Roughing filtration is a pretreatment method and should not be used as a single step treatment process. The process may achieve up to 2 log reduction value [LRV] for bacteria (with performance varying depending on the filter medium and coagulant used [WHO, 2022a]), as well as colour, and some organic matter when operated and maintained optimally. The resulting sludge produced during filtration should be treated as a waste product and disposed of appropriately and in-line with local regulations to minimize health and environmental concerns.

+ Advantages

- Does not require the use of chemicals or mechanical equipment
- Can be constructed with local resources
- Requires relatively low maintenance
- Has low operational costs

- Disadvantages

- Performance may vary significantly depending on the filter design, maintenance practices, and raw water characteristics
- Cannot treat stable suspensions with high concentrations of colloidal matter
- Inefficiently removes colour compared to other pre-clarification methods
- Requires more time and resources for installation than coagulation and sedimentation method

→ References and further reading materials can be found on page 213.

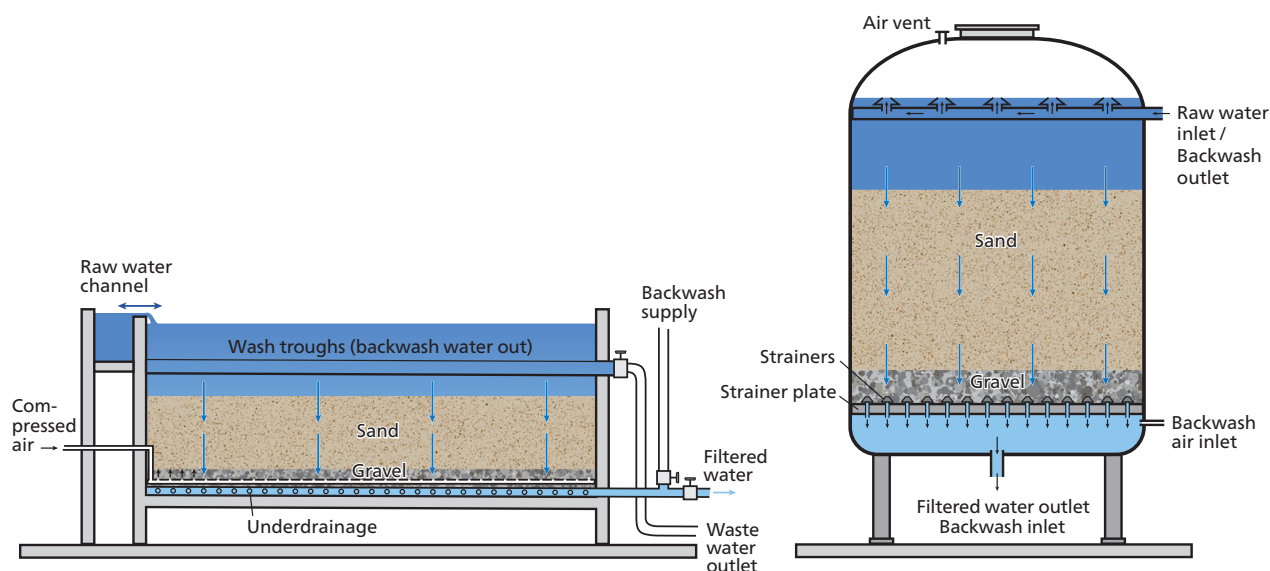
T.1.2 Rapid sand filtration

Applicable to systems
2, 3, 7, 8

Management level
Community, centralized

Local availability of technology
or components
Yes

Technology maturity level
Established technology



Rapid sand filters remove suspended and colloidal solids from turbid water. The water passes through the filter media (sand grain size typically ranging from 0.2–2 mm), and solids are trapped by, settle onto, or adsorb onto the sand material. Rapid sand filters should be installed after coagulation and/or sedimentation and before disinfection (e.g. chlorination, ultraviolet (UV) light disinfection).

Rapid sand filters are applied in a variety of treatment trains. Conventional filtration consists of coagulation/flocculation/sedimentation/rapid sand filtration (T.1.4 Coagulation/flocculation/sedimentation and T.1.2 Rapid sand filtration) and can be applied to any surface water source, including those with high and varying turbidity and colour. Water with a better initial quality, such as from a dam or lake (turbidity < 15 NTU), can also be treated by direct filtration including coagulation/flocculation/rapid sand filtration (T.1.5 Coagulation/flocculation/filtration). Finally, two-stage filtration assembles coagulation/roughing filtration/rapid sand filtration and is typically used in small packaged treatment plants with raw water turbidity < 100 NTU.

Preceded by a coagulation step, rapid sand filters remove 70–90% of suspended solids and colloidal material. Without pretreatment, the removal can be significantly lower. Under optimal operational conditions rapid sand filtration can achieve up to 4 log reduction

value (LRV) for bacteria and viruses, and up to 3 LRV for protozoa (with performance varying depending on filter media, coagulation pretreatment, and general operation and maintenance conditions [WHO, 2022a]).

Rapid sand filters are available in up- and downflow mode, with filtration run by pumping (pressurized filtration) or gravity. For decentralized applications, gravity downflow filters are common because of their easier inspection and maintenance. These downflow filters consist of a basin or tank containing the filter media and a gravel support at the bottom, a manifold and/or underdrain system to collect the filtered (or clear) water, and troughs to collect water from the backwash (i.e. wash water). Additionally, a pump is needed to power the filter backwash and/or to distribute the filtered water. Filtered water is typically pumped to and stored in a water tower (overhead tank, e.g. D.6 Storage tanks or reservoirs). This water can then be distributed by gravity to consumers or back to the filter for backwashing. Chlorine or other oxidants may be added in certain contexts prior to rapid sand filtration or prior to the combined coagulation/filtration process to remove inorganic contaminants such as iron and manganese, reduce organic matter, and reduce biological growth within the sand filters.

Rapid filters are operated at a typical filtration velocity of 10 m/h (range 1–50 m/h), which is higher than that of slow sand filtration (approximately 0.1 m/h). The respective supernatant water height, correspond-

ing to the water level above the filter media, varies from 0.6–2.5 m. The water height depends on the type of flowrate control (i.e. inflow weir or outflow valve). For decentralized drinking-water treatment, monolayer sand filters or dual media filters are most commonly used, the former being simpler and the latter being more robust and reliable. The simplest monolayer rapid sand filter uses, for example, a sand layer of 0.6–0.8 m with mean grain sizes of 0.4–0.8 mm. The required uniformity of the filter media should be assured by sand sieving. In more advanced dual media filters operated in downflow mode, the bottom layer consists of 0.2–0.3 m of sand (as before) and the top layer contains 0.5–1.8 m of either anthracite or granular activated carbon with mean grain sizes of 0.8–2.0 mm.

Applicability and adequacy

Rapid sand filtration is applicable when the turbidity of the raw water needs to be reduced for adequate disinfection and to improve the aesthetic quality of the water. These systems can typically be constructed from local materials. The required sizes for a community water supply range from a few 100 L plastic barrels to several hundred m³/h. The latter is most often built from concrete, local sand, and local piping and valves (i.e. PVC or cast iron).

Operation and maintenance

Rapid sand filtration requires a trained operator to maintain the proper filtration and backwash rates, to check the filtered water quality, and to conduct periodic cleaning and repair. Backwashing is required to remove retained solids, which otherwise lead to filter clogging, turbidity breakthrough, or loss of pressure (or head loss). Usually, routine operation involves regular backwashes, for example, every 1 to 4 days depending on the influent water quality and flow rate. In general, the higher the media layer, the longer the filter can run.

In addition to time, other important triggers for backwashing include filter effluent quality (e.g. turbidity) and pressure (or head loss) across the filter. Filter backwashing is performed with treated water. During backwashing (in upflow mode), the filter bed is expanded such that previously retained fine particles can be released into the wash water. Meanwhile, the operator must ensure that the backwash flowrate is high enough to expand the filter bed, yet not so high as to wash out the filter material. This optimal flowrate typically ranges between 12–90 m/h. Following backwashing, the filter bed experiences a ripening period, during which sub-optimal filter performance is likely. This can be managed by discarding the filtered water to waste during this period. Additionally, the operator needs to regularly check the turbidity of the filtered water to ensure adequate treatment performance. Ideally, this would be monitored online (with corresponding exceedance alarms) or regularly (e.g. daily, depending on the

local context) using a turbidity meter. Finally, the filter media should be replaced after several years, which can be done by manually excavating the media with a shovel. All valves should be opened and closed completely at least once per year. When damaged or malfunctioning, repair or replacement requires a mechanic or plumber.

Health and environmental aspects/Acceptance

The wash water from rapid sand filtration may be turbid and contain harmful microorganisms, so it should be disposed of appropriately and in line with local health and environmental requirements to avoid potential health and ecological impacts downstream. Since the wash water may contain bacteria, viruses, or protozoa, it should not be used for other purposes like washing or bathing. For large community and centralized water treatment plants, wash water should be considered as wastewater and treated as such either on-site or discharged to a sewer for subsequent treatment at a local wastewater treatment plant. In water-scarce settings, the wash water may be recycled back to the head of the water treatment plant. To minimize the risk of microbial contamination from this practice, backwash water should be treated and adequately disinfected (via UV light disinfection where there is a risk from protozoa) in a separate wash water system before being recycled back to the head of the plant (refer to T.1.4 Coagulation/flocculation/sedimentation for an example of a wash water system).

⊕ Advantages

- Does not require the use of chemicals (but pre- and post-treatment do)
- Can be constructed with local resources
- Does not require a high degree of technical capacity for operation
- Serves as a biological filter for the removal of organics (if chlorine is not used upstream)

⊖ Disadvantages

- Requires reliable operation and monitoring on a daily basis
 - Requires proper hydrodynamic design to avoid exceeding the maximum filtration rate, leading to poor filtered water quality
 - Varies largely in its removal of microorganisms, suspended solids, turbidity, and colour depending on the operational parameters
 - Removes only a limited amount of colloids, organics, and colour without upstream coagulation/flocculation/sedimentation
-

→ References and further reading materials can be found on page 213.

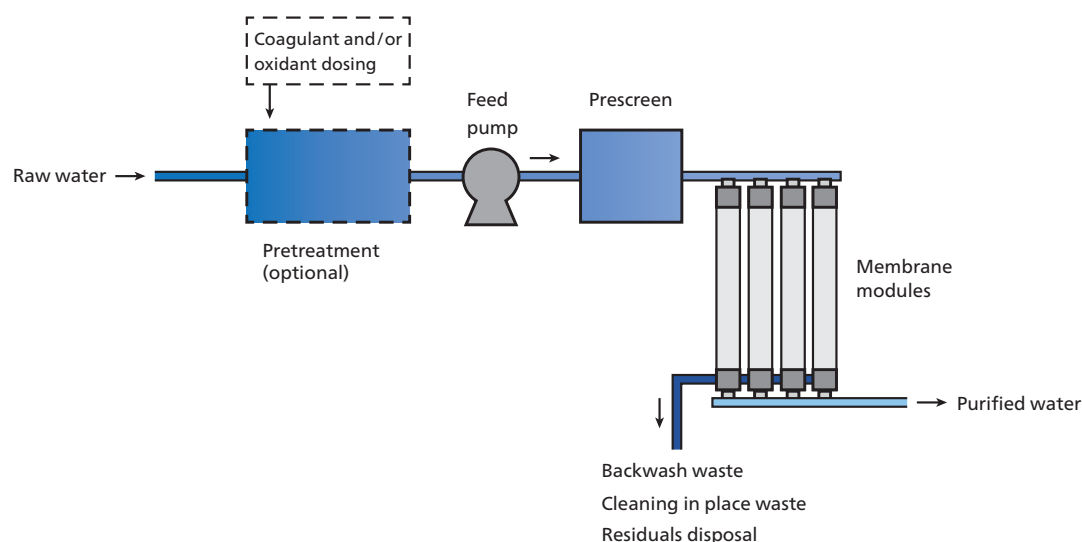
T.1.3 Microfiltration

Applicable to systems
2, 3, 6, 7, 8

Management level
Neighborhood, community,
centralized

**Local availability of technology
or components**
Setting specific, membrane modules
may only be regionally available

Technology maturity level
Established technology



Microfiltration (MF) is used to retain particles and microorganisms that are larger than the pore size of the membrane. These membranes are polymeric or ceramic, with a pore size ranging from 0.1–10 μm . Depending on the pore size, optimal operation may remove protozoa and bacteria up to 6 log reduction value (LRV), with up to 4 LRV removal for viruses (WHO, 2017a).⁹ Since the pore size of MF membranes is typically larger than the size of viruses, microfiltration alone should not be used for disinfection purposes.

The pressure difference between the input stream (feed) and filtrate (permeate) is the driving force of microfiltration. Microfiltration can be operated either under constant pressure or constant flow conditions. The operating transmembrane pressure that is typically used varies from 0.1–1 bar. During continuous operation, particles and microorganisms larger than the pore size are retained on the membrane surface, forming a cake layer. Smaller particles and dissolved organic matter can penetrate into, and adsorb onto the membrane pores. Both processes reduce the flow of water through the membrane when operated under constant pressure or increase the transmembrane pressure when operated under a constant flow. The formation of the cake layer and deposition of organic matter within the pores of the membrane causes fouling. Therefore, MF systems re-

quire periodic cleaning by backflushing and/or chemical treatment (see operation and maintenance) or, in some cases, pretreatment or the addition of coagulants.

There are different types of membrane fouling. Reversible fouling can be removed by backflushing alone whereas irreversible fouling remains after backflushing though can usually be partly removed by chemical cleaning. The composition of organic and particulate matter in the water defines the extent of both types of fouling. The presence of humic substances, the main organic compounds in soil, peat, and coal, and biopolymers in water usually increases irreversible fouling. Most commercial MF membranes are made of polymer materials, but ceramic membranes are also available.

There are three major types of membrane modules: hollow fiber modules, spiral wound modules, and flat sheet membrane modules. In drinking-water production, mostly hollow fiber modules are used since they are the most compact as well as low cost. They also have a lower energy consumption compared to other module configurations.

Applicability and adequacy

Membrane modules are usually supplied by membrane producers as single units (usually 10–40 m² of membrane surface per unit). Engineering companies

and manufacturers then assemble the units in module racks and integrate these into large- or medium-scale drinking-water treatment facilities and/or packaged systems. Large scale MF treatment plants typically include pre- or post-treatment units, such as coagulation and/or disinfection. During periods of high water turbidity, in-line coagulation using iron salts can be used, which can also be automated based on on-line monitoring (e.g. turbidity).

Typically, drinking-water treatment plants apply ultrafiltration (UF) (see T.2.5 Ultrafiltration), and MF is therefore used as a pretreatment for reverse osmosis or to reduce turbidity for subsequent disinfection by other methods. In such cases, MF is typically applied where efficient and cost effective automated operation is required and only limited space is available. Skilled operators are required for the effective operation of MF plants. For large community, decentralized, and centralized systems, ongoing technical support from the manufacturer (including on-site assistance) should be guaranteed, since the maintenance and repair of automated systems require process engineering skills and experience with the individual design features of the systems.

Operation and maintenance

Fouling necessitates periodic membrane cleaning. In automated MF systems, membranes are cleaned by backwashing and/or adding chemical agents that remove the contaminants accumulated on the membrane. During the backwashing process, the direction of the water flow is reversed using high pressure for a certain time interval. This removes the cake layer from the membrane surface and flushes the contaminants out in a concentrated waste stream (retentate). Depending on the manufacturer's specifications and the source water characteristics, membrane backwashing is typically required from every few minutes to every few hours.

Some fouling agents cannot be removed by backwashing alone, but can be chemically detached. Cleaning agents include caustic soda, acids such as citric acid, and/or hypochlorite solutions. These chemicals should not compromise the membrane material or be used at concentrations above what is recommended by the manufacturer (e.g. the sodium hypochlorite concentration should generally not exceed 500 mg/L free chlorine during cleaning). In automated systems, a skilled operator or experienced engineer optimizes the backwash/cleaning intervals in the commissioning phase. Chemical cleaning may also be conducted manually, where the membrane is soaked in cleaning agent.

Over time, MF membranes experience some degree of fouling that can no longer be removed through backwashing or chemical cleaning. Consequently, the membrane must be replaced (generally every 7–10 years).

The time until replacement is usually defined by manufacturer and assessed during their on-site technical support visits based on performance (e.g. turbidity breakthrough, pressure levels) and the extent of irreversible fouling.

Health and environmental aspects/Acceptance

The disposal of backflush water must be carefully considered as it may contain a concentrate of the (microbial) contaminants found in the feed water when hypochlorite is not used during backwashing.

⊕ Advantages

- Removes turbidity effectively
- Provides a barrier to bacteria and protozoa
- Operates constantly and reliably through automation and the treatment of water of variable quality
- Uses a smaller land area due to transportable and mobile membrane units, as compared to conventional filtration systems

⊖ Disadvantages

- Has relatively high investment costs and considerable operational and maintenance costs
- Requires skilled personnel for operation and maintenance
- Requires a reliable power supply due to the need for continuous operation to guarantee optimal membrane performance

→ References and further reading materials can be found on page 213.

9 The LRVs achieved in practice will vary depending on the integrity of the filter medium and filter seals, resistance to chemical and biological ("grow-through") degradation, and general operation and maintenance conditions (WHO, 2017a).

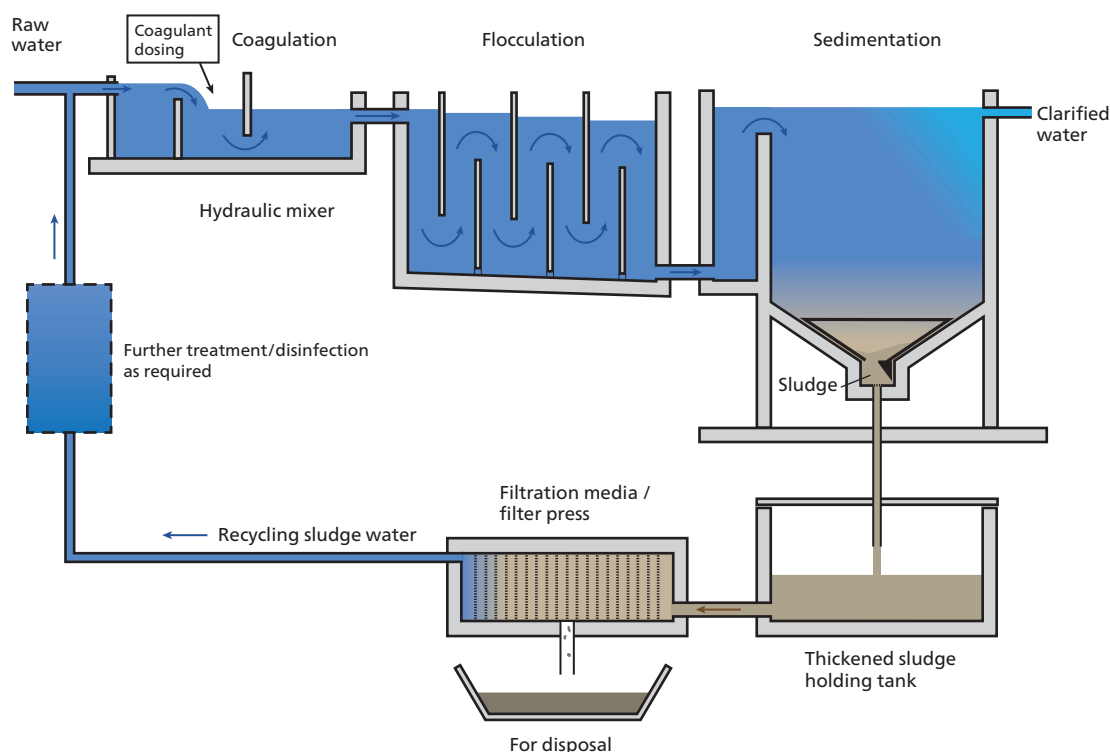
T.1.4 Coagulation/flocculation/sedimentation

Applicable to systems
2, 3, 7, 8

Management level
Community, centralized

Local availability of technology
or components
Yes

Technology maturity level
Established technology



Coagulation/flocculation is a pretreatment step to reduce suspended and colloidal solids, organics, and colour. A coagulation agent is added to the raw water, which aggregates the finely dispersed particles into larger agglomerates (or flocs), that can then be removed by sedimentation or filtration (T.1.5 Coagulation/flocculation/filtration).

Most fine particles dispersed in water are negatively charged and consequently repel each other. In this way, they remain suspended instead of settling. Coagulation agents can neutralize this charge and thus destabilize the particle suspension (called coagulation). After charge neutralization, inter-particle attractive forces attach individual particles into larger flocs (called flocculation). Eventually the particles become large enough to settle via gravity.

Coagulation/flocculation/sedimentation is typically applied as a pretreatment step to subsequent downstream treatment. The process can remove microorganisms to a degree when operated at optimally, achieving up to 2 log reduction value (LRV) for bacteria and protozoa and up to 3 LRV for viruses (with performance varying depending on coagulation conditions,

and general operation and maintenance conditions [WHO, 2022a]). However, conventional coagulation/flocculation/sedimentation should be followed by filtration and disinfection.

Common coagulants include ferric and alumina salts mainly combined with chlorides or sulfates, such as a solution of ferric chloride (FeCl_3) or poly aluminum chloride (PACl). In low-income countries, the natural and locally available solid alum (natural compound containing aluminum sulfate) is often used. Because the pH of raw water strongly influences the process efficiency, it can be adjusted to the optimal level of around pH 8 for ferric coagulants and around pH 6 for aluminum coagulants. It is important that coagulant dosage is routinely determined to account for a variable quality of source water (see jar test below), because a sub-optimal dosage (i.e. under-/overdosage) can result in poorly clarified water. Typical dosages for ferric chloride (hexahydrate) and alum range from 5–150 mg/L and 10–250 mg/L, respectively, depending on the raw water quality (e.g. turbidity, colour, pH).

A slurry or solution of coagulants should be added by a dosing pump. Intense rapid mixing (typically 2–5 minutes), often also known as flash mixing, distributes

the coagulant in the raw water. Floc formation is achieved through mixing/agitation in a flocculation chamber at decreasing speeds (from higher to lower) for typically 10–80 minutes. The formed flocs are then large enough to settle via gravity in a sedimentation basin¹⁰ for typically 90–180 minutes.

Applicability and adequacy

On the smallest scale, flocculation can be performed batch-wise in buckets or barrels. Dose pumping is the most reliable in larger flow-through systems, but this requires power and that the solid alum be dissolved before dosage control. Mixers are normally electrically driven, though overflow weirs and static mixers are passive mixing approaches (i.e. do not require power) for coagulation and flocculation, respectively.

Most sedimentation basins are circular or rectangular, and the flow is horizontal. In rectangular systems, the depth and width of the flocculation basin should be similar to the that of the sedimentation basin. The depth should typically not exceed 5 m. In the case of limited land availability, lamella plates¹¹ can be installed in the sedimentation basin to increase settling efficiency and capacity. To facilitate settling, the water must not be disturbed/mixed in the sedimentation basin. An overflow weir is usually used at the outlet to uniformly distribute the flow and minimize the resuspension of particles.

Operation and maintenance

For efficient operation and performance, it is critical to optimize the chemical dosage of the coagulants and flocculants and ensure the ideal pH via the addition of acid or base (alkali) as required. To determine the minimum dosage of the chemicals required for coagulation/flocculation to achieve the desired water quality targets, the simple laboratory jar test should be performed. This tests the actual raw water and should be conducted routinely, minimally at the start of both the dry and rainy season. Ideally, jar tests should be conducted more frequently where the raw water quality varies, particularly during heavy rain events when the source water quality can rapidly deteriorate. During these heavy rain events, the operator also needs to ensure that the elevated flow rate entering the sedimentation basin does not prevent flocs from settling. This can be done by diverting the flow or closing the intake completely.

Quality control monitoring of the raw and clarified water should be routinely carried out to optimize the process (e.g. turbidity, pH, colour, flow rate). Ideally, monitoring should be carried out online for larger systems (with corresponding exceedance alarms). In smaller systems, grab samples should be analysed daily to weekly, at a minimum, depending on the source water quality characteristics and variability.

The dosing pump and mixers need regular inspection and maintenance (particularly if installed outside). In humid climates, special attention must be given to corrosion of these units.

Finally, the settled sludge must be removed regularly either manually or via an underdrain, typically every couple of weeks or months depending on the source water quality. Drained sedimentation basins can be cleaned manually with a shovel. On-site sludge treatment typically involves dewatering the sludge (e.g. via gravity thickeners and presses) to produce a dewatered sludge cake suitable for transportation and disposal or reuse.

Health and environmental aspects/Acceptance

Most coagulants and the acids and bases used to adjust the pH must be treated with care since they can be corrosive (e.g. FeCl_3). The sludge produced in the sedimentation basin can cause health concerns, as it may comprise pathogens and/or heavy metals depending on the raw water quality. The produced sludge needs usually subsequent treatment, degradation, and safe disposal in a landfill. If water from dewatered sludge is recycled back into the system, it should be treated/disinfected (e.g. via UV disinfection where there is a risk from protozoa) before being returned to the head of the plant.

+ Advantages

- Lower installation costs and long lifetime
- Lower operational costs
- Consists of widely available materials for construction and operation (e.g. alum)

– Disadvantages

- Requires a lot of land for sedimentation
- Requires skilled operator for raw water quality monitoring, dosage, and chemical handling
- Has poor treatment efficiency in case of under-/overdosage
- Requires continuous supply of coagulant and power for mixing

→ References and further reading materials can be found on pages 213 and 214.

¹⁰ Dissolved air floatation may be used as an alternative to sedimentation in certain settings (i.e. use of micron-sized air bubbles that attach to flocs, forming a sludge blanket at the surface of the tank which can be subsequently removed by a hydraulic “float-off”).

¹¹ A series of inclined plates that provides a large surface area for floc settling in a small footprint.

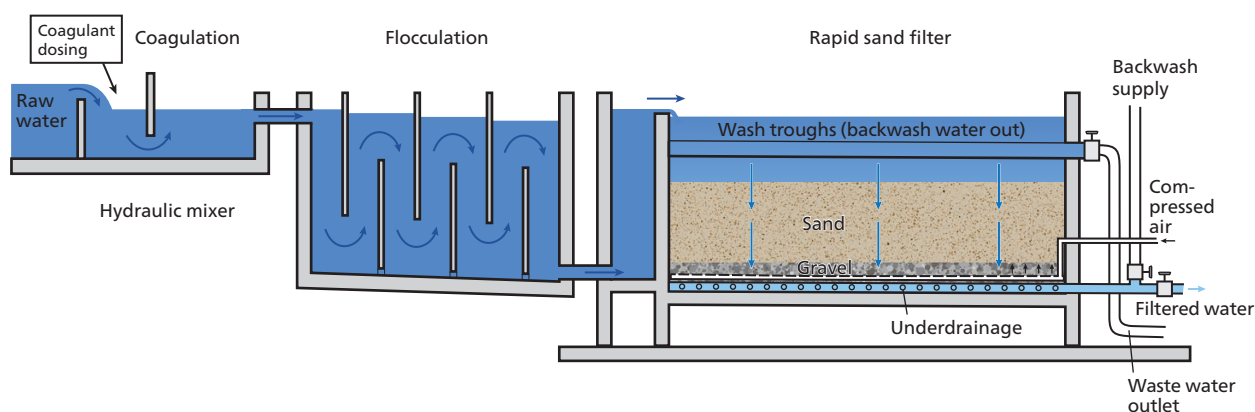
T.1.5 Coagulation/flocculation/filtration

Applicable to systems
2, 3, 7, 8

Management level
Community, centralized

Local availability of technology
or components
Yes

Technology maturity level
Established technology



Coagulation/flocculation is a pretreatment step required to reduce suspended and colloidal solids, organics, and colour. A coagulation agent is added to the raw water, which aggregates the finely dispersed particles into larger agglomerates (or “flocs”), that can then be removed by sedimentation (see T.1.4 Coagulation/flocculation/sedimentation) or filtration.

Most fine particles dispersed in water are negatively charged and consequently repel each other. In this way, they remain suspended instead of settling. Coagulation agents can neutralize this charge and thus destabilize the particle suspension (called coagulation). After charge neutralization, inter-particle attractive forces attach individual particles into larger flocs (called flocculation). Finally, the particles become large enough to be filtered out.

Although this process can remove microorganisms to a degree when operated at optimal conditions, conventional coagulation/flocculation/filtration (also called direct filtration) should be followed by disinfection, such as with chlorine (see T.2.1 Chlorination) or UV (see T.2.3 Ultraviolet (UV) light disinfection). Coagulation/flocculation/filtration is generally only appropriate for higher quality source waters (e.g. turbidity < 15 NTU).

Common coagulants include ferric and alumina salts mainly combined with chlorides or sulfates, such as a solution of ferric chloride (FeCl_3) or poly aluminum chloride (PACl). In low income countries, the natural and locally available solid alum (natural compound containing aluminum sulfate) is often used. Because

the pH of raw water strongly influences the process efficiency, it can be adjusted to the optimal level of around pH 8 for ferric coagulants and around pH 6 for aluminum coagulants. It is important that coagulant dosage is routinely determined to account for a variable quality of source water (see jar test below), as a sub-optimal dosage (i.e. under/overdosage) can result in poorly clarified water. Typical dosages for ferric chloride (hexahydrate) and alum range from 5–150 mg/L and 10–250 mg/L, respectively, depending on the raw water quality (e.g. turbidity, colour, pH).

A slurry or solution of coagulants should be added by a dosing pump. Intense rapid mixing (typically 2–5 minutes), often also known as flash mixing, distributes the coagulant in the raw water. Floc formation is achieved through mixing/agitation in a flocculation chamber at decreasing speeds (from higher to lower) for typically 10–80 minutes. The final filtration step may be either rapid sand filtration (see T.1.2 Rapid sand filtration) or microfiltration (see T.1.3 Microfiltration). Rapid sand filtration is more suitable for decentralized drinking-water treatment because of the lower investment costs and availability of spare parts. It is usually operated by gravity in downflow mode. For more details refer to T.1.2 Rapid sand filtration.

Membrane filtration usually requires filtration and backwash pumps, leading to higher investment and operational costs than rapid sand filtration. However, the filtered water is of higher quality (i.e. higher removal rates for microorganisms, turbidity, organics, and colour), and the required coagulant dosage may be lower. For more details, refer to T.1.3 Microfiltration. In

some membrane filtration systems, in-line coagulation is used. In such systems, the coagulants are introduced prior to filtration and are often mixed in the pipe (via static mixing) followed directly by membrane filtration.

Applicability and adequacy

Dose pumping is most reliable in large flow-through systems, but these systems require power and that the solid alum be dissolved before dosage control. Mixers are normally electrically driven, though overflow weirs and static mixers are passive mixing approaches (i.e. do not require power) for coagulation and flocculation, respectively. To backwash the filter, the system must have a pump and/or a water tower. Because it is normally applied to higher quality source waters with lower turbidity, this process results in less backwashing and sludge production (and lower associated costs for power and sludge processing/disposal) than conventional coagulation/flocculation/sedimentation (see T.1.4 Coagulation/flocculation/sedimentation).

Operation and maintenance

For efficient operation and performance, it is critical to optimize the chemical dosage of the coagulants and flocculants and ensure the ideal pH via the addition of acid/base as required. To determine the minimum dosage of the chemicals required for coagulation/flocculation to achieve the desired water quality targets, the simple laboratory jar test should be performed. This test uses the actual raw water and should be conducted routinely, minimally at the start of both the dry and rainy season. Ideally, jar tests should be conducted more frequently where the raw water quality varies, particularly during heavy rain events when the source water quality can rapidly deteriorate. During these heavy rain events, the operator also needs to ensure that the elevated flow rate entering the sedimentation basin does not prevent flocs from settling. This can be done by diverting the flow or closing the intake completely.

Quality control monitoring of the raw and clarified water should be routinely carried out to optimize the process (e.g. turbidity, pH, colour, flow rate). Ideally, monitoring should be carried out online for larger systems (with corresponding exceedance alarms). In smaller systems, grab samples should be analysed daily to weekly, at a minimum, depending on the source water quality characteristics and variability.

The dosing pump and mixers need regular inspection and maintenance (particularly if installed outside). In humid climates, special attention must be given to corrosion of these units.

Rapid filters and membranes both require periodic backwashes and cleaning. For details, refer to T.1.2 Rapid sand filtration and T.1.3 Microfiltration, respec-

tively. On-site sludge treatment is described in T.1.4 Coagulation/flocculation/sedimentation.

Health and environmental aspects/Acceptance

Most coagulants and the acids and bases used to adjust the pH must be handled with care since they can be corrosive (e.g. FeCl_3). The sludge produced in the sedimentation basin can cause health concerns, as it may contain high levels of pathogens and/or heavy metals depending on the raw water quality. Usually, the produced sludge needs subsequent treatment, degradation, and safe disposal in a landfill. If water from dewatered sludge is recycled back into the system, it should be treated/disinfected (e.g. via UV disinfection where there is a risk from protozoa) before being returned to the head of the plant.

⊕ Advantages

- Lower installation costs and long lifetime
- Lower operational costs (rapid filters)
- Consists of widely available materials for construction and operation (alum)
- Requires less land, capital (only rapid filters), and operational costs, and produces less sludge compared to coagulation/flocculation/sedimentation

⊖ Disadvantages

- Requires skilled operator for proper dosage, chemical handling, and filter backwash
 - Has poor treatment efficiency in case of under/overdosage
-

→ References and further reading materials can be found on page 214.

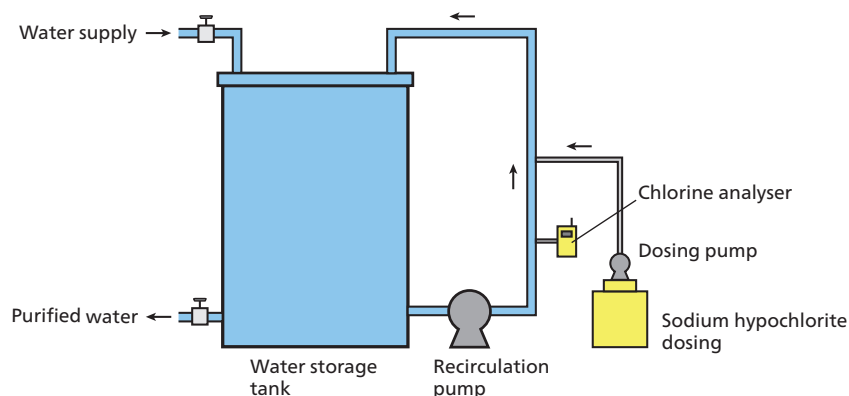
T.2.1 Chlorination

Applicable to systems
2, 3, 6, 7

Management level
Household, neighborhood,
community, centralized

**Local availability of technology
or components**
Yes

Technology maturity level
Established technology



Chlorination consists of the addition of chlorine compounds to water. Under optimal conditions, chlorine can inactivate bacteria and many viruses and can provide some residual protection against low-level microbial recontamination and growth, including as a result of user practices.

The three most commonly used forms of chlorine are:

- Chlorine gas, which is pure elemental chlorine that is supplied as liquefied gas in pressurized containers. It is usually injected under pressure or through a vacuum-operated solution feed system into the water line using precise dosing equipment. The application of chlorine gas requires special safety precautions. It is thus only recommended for larger and automated installations (i.e. municipal water treatment plant) with skilled personnel and proper process controls and safety measures in place.
- Sodium hypochlorite (NaOCl), also called bleach, which is commercially available as a 10–15% solution. The shelf life of liquid sodium hypochlorite is limited. Depending on the size of installation, it can be metered in the receiving stream with a dosing pump or gravity. Sodium hypochlorite can also be produced on-site through the electrolysis of salt in an open cell or a membrane-based system (T.2.2 On-site electrochlorination).
- Calcium hypochlorite ($\text{Ca}[\text{OCl}]_2$), which is available as “powdered chlorine” or “bleach powder” in a concentration of 25–30%, high test hypochlorite (HTH) with a concentration of 65–70%, or solid chlorine compressed into tablets or briquettes and combined with different additives. Powdered calcium hypochlorite needs to be dissolved prior to use or can be added as a powder directly into the receiving water when there is adequate mixing. Solid calcium hypochlorite is often dosed through special contact

erosion systems, where water passes through the contactor and slowly dissolves the tablet to form a solution of a desired concentration. Solid hypochlorite is usually more expensive than other forms.

The concentration of chlorine in water that is available for disinfection and/or oxidation is referred to as active chlorine. Upon disinfection/oxidation this active chlorine is consumed by inorganics, ammonia, and organic matter in the water (often referred to as chlorine demand), and the concentration subsequently decreases. The dosage of active chlorine usually ranges from 1–6 mg/L, depending on the quality of the water and corresponding chlorine demand.

For effective disinfection, WHO recommends a residual free chlorine concentration (i.e. active chlorine remaining after being in contact with the water during treatment) of ≥ 0.5 mg/L after at least 30 minutes of contact time at $\text{pH} < 8$. A free chlorine residual concentration of ≥ 0.2 mg/L must be maintained throughout the distribution system until the point of delivery to minimize the risk of microbial recontamination and growth during distribution and storage. The chlorine concentration (C) multiplied by the contact time (t) yields the Ct value. In general, chlorine is effective against bacteria and many viruses at typical Ct values applied in water treatment plants. Ct values for different microorganisms can be found in LeChevallier & Au (2004). Chlorine is ineffective against several protozoa including *Cryptosporidium* oocysts, at concentrations and contact times practical for water treatment processes.

Applicability and adequacy

Chlorination is the most common disinfection method worldwide, applied at all treatment scales ranging from households to centralized treatment. Chlorine can be added to the water at various stages of treatment:

Pre-oxidation: Chlorine is added as an oxidizing agent in a pretreatment step designed to remove inorganic contaminants, such as iron and manganese. Organics may also be removed, which can form undesirable disinfection by-products. Furthermore, trivalent arsenic (arsenite) can be oxidized to pentavalent arsenic (arsenate), which is more easily removed by iron oxides.

Primary disinfection: Chlorine is added as a final treatment step (i.e. typically added after filtration) to disinfect the water and provide a free chlorine residual concentration during distribution and storage.

Secondary disinfection: Chlorine is added during distribution/storage within the network via “booster” chlorination stations, or passive in-line chlorination devices, to ensure an adequate residual concentration is maintained to the point of use. Chlorine disinfection may also be applied at the household level (H.4 Chemical disinfection).

For disinfection the ideal pH is less than pH 8. Above pH 8, the effectiveness of chlorine is reduced such that more contact time or a higher concentration may be required for effective disinfection. To balance other water quality considerations with disinfection, the optimum pH for drinking-water is generally considered to be between pH 6.5 and 8.5.

If dose pumping is applied, power (e.g. electricity) is required. The gravity feeding of a hypochlorite solution also requires careful operation given the risk of sub-optimal dosing. It is recommended that the influent water turbidity is below 1 NTU to ensure sufficient disinfection. However, keeping the turbidity below 1 NTU is not always possible in lower-resource settings; in such cases, the aim should be to keep turbidities below 5 NTU. At turbidities above 1 NTU, higher disinfection doses or contact times will be required to ensure that the adequate Ct value is achieved (WHO, 2017c).

Operation and maintenance

Routine operation includes the dosing of hypochlorite solutions (pre-dissolved $\text{Ca}[\text{OCl}]_2$ or NaOCl) either by a gravity dosing system or via a dosing pump. Pumping provides better dosage control. The chlorine dosage and residual free chlorine levels should be monitored regularly in the treated water and during storage/distribution by a trained operator or technical support. This should ideally be online with corresponding exceedance alarms, or grab samples need to be analysed at least once a day with a chlorine test kit.

Since chlorine is very corrosive, special attention must be given to maintaining the dosing and downstream equipment (stock solution storage container, pumps, valves, pipes).

Chlorine may degrade over time or if stored improperly (e.g. in direct sunlight, open to the environment). For this reason, best practice stock management (i.e. following “first in, first out” principles) and storage (i.e. store away from direct sunlight, excessive humidity, and

high temperatures in sealed, corrosion-resistant containers) is required.

Health and environmental aspects/Acceptance

Chlorination is by far the most applied disinfection method, and thus has a high general acceptance. Consumers vary in their taste/odour threshold for chlorine and can object to concentrations as low as 0.3 mg/L, which can lead them to seek non-chlorinated, and therefore less safe, sources of drinking-water. Effective communication and consumer engagement is needed to manage such concerns to assure consumers regarding the health benefits of drinking chlorinated water.

Skin and eye contact should be avoided by using personal safety equipment (protective glasses, gloves, and cotton coat/clothing). The respiration of chlorine gas can be avoided with adequate ventilation. Proper operator training assures safe handling.

Chlorine overdosage, high organic content in the water, and/or long detention times during storage and distribution may contribute to the formation of disinfection by-products, such as trihalomethanes. The inadequate storage of hypochlorite may result in the formation of chlorite. These disinfection by-products should be minimized due to potential health concerns associated with long-term exposure. However, the longer-term potential risks to health from these by-products are low in comparison with the confirmed acute risks associated with inadequate disinfection, and disinfection should therefore not be compromised in attempting to control disinfection by-products.

+ Advantages

- Low installation and operational costs
- Locally available (liquid or solid)
- Can inactivate bacteria and viruses when operated optimally
- Easy to use compared to other treatment technologies including other disinfectants
- Provides some residual protection

– Disadvantages

- Ineffective against *Cryptosporidium* oocysts (requiring additional barriers for protection)
- Requires trained operator and equipment
- Requires higher doses and/or contact times if turbidity is elevated
- Requires regular inspection/replacement due to equipment corrosion
- Users may object to taste and odour
- Deteriorates over time and when stored improperly

→ References and further reading materials can be found on page 214.

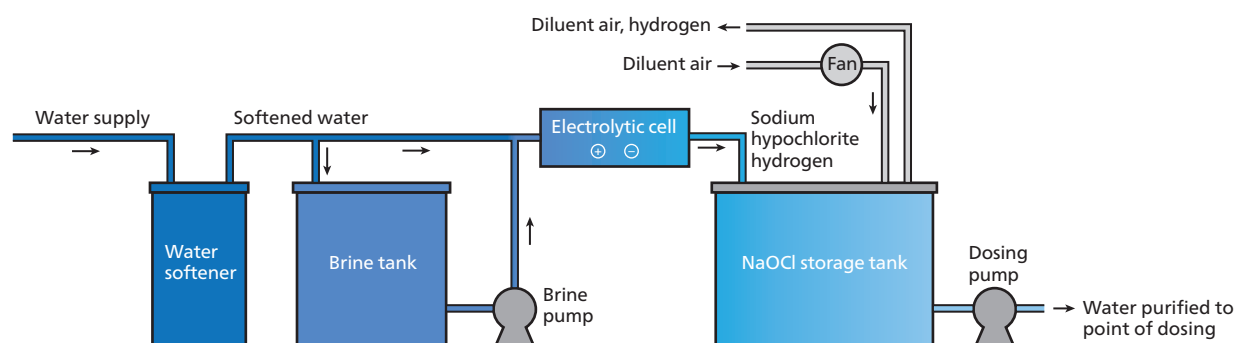
T.2.2 On-site electrochlorination

Applicable to systems
2, 3, 6, 7

Management level
Household, neighborhood,
community

**Local availability of technology
or components**
No

Technology maturity level
Established technology



On-site electrochlorination, also known as the electrolytic generation of sodium hypochlorite, involves the electrolysis of aqueous sodium chloride (common salt).

During electrolysis, a direct electric current drives chemical reactions that are otherwise non-spontaneous. Chemical reactions occur at two electrodes, the anode and the cathode. At the anode, the chloride ion is converted into chlorine. At the cathode, hydrogen gas is produced for a pH increase. The chlorine gas reacts immediately (in an open cell system) or at a later stage (membrane system) with hydroxide ions to form a hypochlorite ion. The sodium hypochlorite solution can be used directly to disinfect and/or pretreat water when operated in continuous mode, or it can be stored in a buffer tank for later use when operated in batch mode. The concentration of chlorine in water that is available for disinfection and/or oxidation is referred to as active chlorine. Upon disinfection/oxidation this active chlorine is consumed by inorganics, ammonia, and organic matter in the water (often referred to as chlorine demand), and the concentration subsequently decreases. The dosage of active chlorine usually ranges from 1–6 mg/L, depending on the quality of the water and corresponding chlorine demand.

In continuous operation mode in open cell systems, incoming raw water usually goes through a softener before being split into two lines. One line goes to the electrolytic cell, and the other line is directed to the brine storage tank. Saturated brine is injected into the softened water, which passes to the electrolytic cell.

Here, a current passes through the electrodes, and sodium hypochlorite and hydrogen are produced. Sodium hypochlorite is then stored in another tank from which it is metered into water. The hydrogen is diluted immediately and is discharged into the atmosphere. There are also systems designed to be operated in a batch or semi-batch mode, which are usually less costly and are considerably less automated.

Applicability and adequacy

On-site electrochlorination can only be used where the raw water is of sufficient quality due to the risk of fouling the electrodes, and these raw water specifications vary for different systems. Usually the following raw water specifications are required: hardness (< 50 mg/L); manganese (< 50 µg/L); iron, fluoride, free chlorine, and cyanides (< 1 mg/L); pH (pH 5–9); lead (< 2 mg/L); bromide (< 50 mg/L); and silica (< 80 mg/L). Where the water quality exceeds these limits, comprehensive pretreatment including the use of a water softener is required. In principle, any type of salt can be used here, but solar salt (i.e. salt produced by evaporation as opposed to mined salt) with a minimum composition of 99.8% sodium chloride (NaCl) and < 0.14% of calcium and magnesium is more suitable.

For large scale on-site systems, a DC power rectifier is usually required. These on-site electrochlorination systems can replace conventional chlorine gas systems, and part of the equipment can be retrofitted to reduce costs. While the installation costs of electrochlorination are generally higher compared to chlorine gas, the operational costs and security efforts

related to assuring the security of chlorine gas transport and storage are considerably reduced compared to chlorine gas. Once the electrochlorination system is installed, the process is not easily scaled-up, as no additional cells can be added without the corresponding scale-up of all the equipment.

Operation and maintenance

The site needs to be prepared by a local on-site engineer. The installation and start-up phase requires the presence of a well-trained service engineer who is provided or trained by a supplier or distributor. Local operators need to be trained during the start-up phase, which usually lasts up to one week, though they are capable of managing the system on their own after the intensive training.

The systems often need to be designed at 20–30% greater capacity to extend the equipment life. Brine tanks are required to maintain a capacity corresponding to a demand of 15–30 days, and the level should be maintained close to the recommended storage amount to avoid automatic shut-down. Leak control as well as careful monitoring of the operating voltage, current, and the relationship between salt usage and operating time should be conducted. Signs of fouling on the electrodes and float switches need to be detected visually, and when detected, a cleaning procedure needs to be initiated. Most systems are supplied with an integrated acid cleaning system, which can be either manual or fully automated. It is important to monitor the water hardness, hypochlorite concentration, and brine concentration.

Health and environmental aspects/Acceptance

On-site electrochlorination reduces the need for handling, transporting, and storing hazardous materials, thus increasing general safety, though a good ventilation system is needed for hydrogen removal and to avoid trapping hydrogen in the pipes. As for other chlorination techniques, the acceptance of chlorine in previously unchlorinated areas might be limited.

⊖ Disadvantages

- Requires skilled operators for operation and maintenance of the unit
- Requires higher capital investment costs compared to chlorine gas systems
- Requires sufficiently experienced equipment supplier
- Requires reliable source of electricity
- Requires good initial water quality to reduce fouling of electrodes

→ References and further reading materials can be found on page 214.

⊕ Advantages

- Functions automatically to a high degree and requires minimal labor
- Reduces risk from handling and storage of hazardous materials
- Reduces dependency on chemical supplies, including their availability, transportation, and costs
- Requires lower operational costs compared to chlorine gas systems

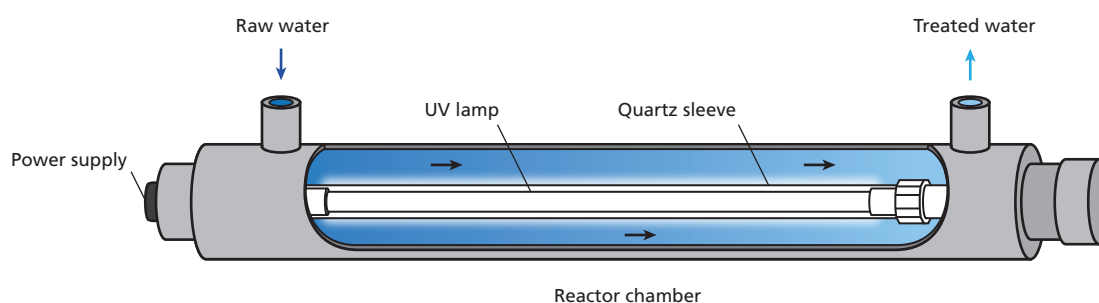
T.2.3 Ultraviolet (UV) light disinfection

Applicable to systems
2, 3, 6, 7

Management level
Household, neighborhood,
community, centralized

**Local availability of technology
or components**
Setting specific, key parts may only
be regionally available

Technology maturity level
Established technology



UV light is a non-chemical approach for water disinfection that is effective against all classes of pathogens and requires only seconds of contact time. It has been successfully used for drinking-water treatment at all scales.

UV disinfection is a physical process whereby emitted photons are absorbed by critical cellular components, such as nucleic acids (DNA and RNA) and proteins, which inhibits normal cellular function and is eventually lethal. Some bacteria are able to repair DNA damage if the radiation is insufficient, especially when exposed to the wavelengths present in sunlight. UV irradiation for water treatment is generated from mercury lamps or UV-light-emitting diodes (LEDs) at different scales. The irradiation is mostly applied at the point of entry and point of use at low flow rates.

For disinfection, wavelengths in the 200–300 nm range (primarily the UVC region) are optimal, with 250–270 nm being ideal. For decentralized drinking-water treatment with UV irradiation, low pressure mercury vapor lamps are typically used, whereas for large-scale systems, low- or medium-pressure mercury vapor lamps are typically used. Low pressure lamps emit a single peak of UV radiation at 254 nm, whereas medium pressure lamps emit polychromatic UV radiation over 185–400 nm and into the visible light range.

A typical municipal scale UV disinfection system includes an array of UV lamps encased in quartz sleeves and submerged in a closed conduit system, which is usually made of stainless steel or sometimes UV-reflecting Teflon.

Water flows across the lamps from one end of the UV system to the other in a matter of seconds, emerging disinfected. The hydraulic retention time is a key factor in the design of the system that ensures the UV radiation exposure time and the lamp output intensity provide the proper UV dose to inactivate the full suite of pathogenic microorganisms. Water quality, specifically the UV transmittance of the water, is a key design parameter.

The UV dose for water disinfection is usually $\geq 40 \text{ mJ/cm}^2$. A typical low dose ($1\text{--}10 \text{ mJ/cm}^2$) UV treatment provides at least 3 log reduction value (LRV) for vegetative bacteria and protozoan parasites, including *Cryptosporidium parvum* and *Giardia lamblia*, with performance influenced by the delivered fluence (i.e. dose, which varies with intensity, exposure time and UV wavelength) as well as turbidity and presence of certain dissolved solutes, and general operation and maintenance conditions [WHO, 2022a]. To inactivate bacterial spores and enteric viruses, higher doses ($30\text{--}150 \text{ mJ/cm}^2$) are required. Only validated UV systems providing the designed dose under typical flow rates and UV transmittance values should be used. The UV transmittance at 254 nm is typically greater than 80% in drinking-water sources. Low UV transmittance (UVT) in water reduces the treatment effectiveness and should be monitored.

Other water quality parameters such as turbidity or suspended solids can reduce the disinfection efficiency by shielding the pathogen targets from the UV light. Inorganic constituents, such as iron or manganese, can foul the lamp and reduce light transmission. Ideally for effective treatment, the turbidity should be $< 5 \text{ NTU}$,

suspended solids <10 mg/L, iron <0.3 mg/L, and manganese <0.05 mg/L. Pretreatment may be required when the water quality parameters exceed the limiting values. Conventional clarification processes, slow sand or rapid sand filtration, membrane filtration, or advanced technologies such as ozonation and activated carbon filtration can be used depending on the composition of the raw water as well as the context.

Applicability and adequacy

Mercury-based UV lamps cover all treatment scales from household application (see H.8 Ultraviolet (UV) light disinfection) to municipal water treatment. UV lamps require a continuous power supply. Since their intensity status and expected remaining lifetime should be monitored by a UV sensor, a minimum system automation is also recommended. This consequently replaces the need for a skilled operator. UV disinfection does not protect from microbial recontamination and regrowth after treatment.

Operation and maintenance

Large-scale UV systems are designed for continuous operation. They should be shut down only if there is no need for treatment for several days. Lamps need to be warmed-up for a few minutes before the system can be restarted.

For community and small-scale systems, daily operation includes switching the lamp on and off depending on the water flow, which is usually a fully automated process. Monitoring of the lamp status should also function automatically. If the operating lamp dose falls below a set-point for validated performance (approximately 70% or less from initial design value), the system needs maintenance typically due to:

- UV-absorbing (dissolved or suspended) matter that may decrease the light penetration, and the reactor should be flushed. Upstream water should be checked for transmittance and turbidity, and if necessary, pretreatment must be improved.
- Foulants that may cover the UV sensor or lamp. The reactor has to be opened, and the sensor, lamp, and inner reactor surface should be cleaned, such as with a soft cloth to avoid scratching and a slightly acidic solution. Some systems have an automated cleaning mechanism that wipes the quartz sleeves around the lamps at regular intervals.
- The UV lamp may have reached the end of its life if none of the above reasons apply. The lamp must be replaced to ensure proper disinfection. The nominal lifetime ranges from 8000–12 000 operational hours (about 1 year of continuous operation) for mercury lamps. For LEDs, the lifespan varies depending on the specifications of the LEDs and manufacturer. At least yearly, the inner surface of the reactor should be inspected and cleaned.

The UV transmittance of raw water may vary over time. This parameter should be measured regularly or monitored online to ensure the level is maintained above the manufacturer's minimum.

Health and environmental aspects/Acceptance

Direct exposure to UV radiation must be avoided. UV radiation can burn the skin and damage the eyes, so it is important for operators to protect their eyes and skin during maintenance and operation. Concern may arise from the lack of residual disinfectant. Hence, treated water should be distributed (constant overpressure in the distribution networks and maintenance of a free chlorine residual) and stored safely (D.4 Small public and community distribution system, D.6 Storage tanks or reservoirs, H.1 Storage tanks or reservoirs). If the lamp breaks, toxic mercury may be released into the environment, potentially causing a health risk for the operator and harming the environment.

⊕ Advantages

- Operates simply and inexpensively
- Requires no supply of chemicals
- Does not change the taste and odour of the water
- Less potential to form disinfection by-products
- Disinfects microorganisms with high chlorine-resistance, such as *Cryptosporidium parvum* oocysts

⊖ Disadvantages

- Requires reliable power supply
- Requires spare parts (mercury lamp)
- Lacks residual disinfectant (safe distribution and storage must be assured)
- Requires pretreatment for turbid and low transmittance waters to increase UV transmittance
- Capital cost of equipment higher than other disinfection systems (e.g. chlorination)

→ References and further reading materials can be found on pages 214 and 215.

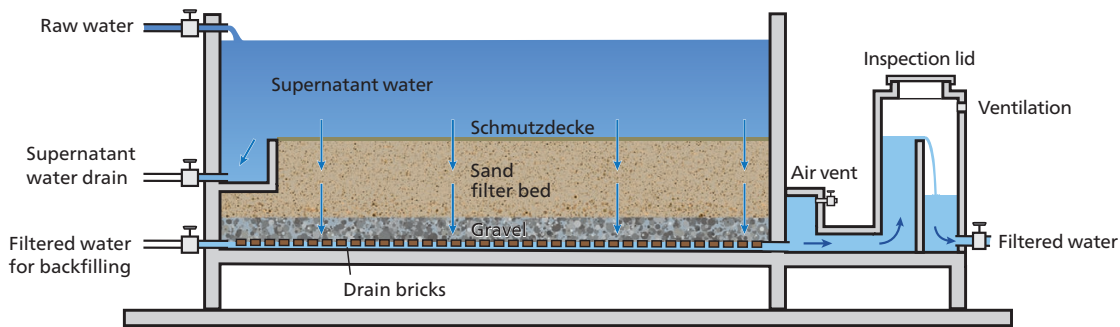
T.2.4 Slow sand filtration

Applicable to systems
2, 3, 6, 7

Management level
Community, centralized

Local availability of technology
or components
Yes

Technology maturity level
Established technology



Slow sand filters (SSFs) remove suspended and colloidal solids from turbid water. This process is characterized by a biologically active upper layer (Schmutzdecke) that forms during filtration and that supports the removal of pathogenic microorganisms (bacteria, protozoa, and viruses). To support this biological activity, a slow water flow rate of about 0.1–0.3 m/h is required. Slow sand filters also require a low inflow turbidity (< 10 NTU) to prevent clogging.

Slow sand filters are downflow filters in which the water passes through a sand layer where it undergoes physical treatment (similar to rapid sand filtration (see T.1.2 Rapid sand filtration) and biological treatment. The Schmutzdecke contains a diverse microbial community that forms during the first weeks of filtration and that is responsible for the biological activity. Predatory microorganisms originating from the source water feed on pathogenic microorganisms and disinfect the water. Run optimally, SSFs can achieve up to 6log reduction value (LRV) for bacteria, 4LRV for viruses and > 5 LRV for protozoa, with performance depending on the presence of the Schmutzdecke, grain size, flow rate, and operating conditions (mainly temperature, pH) (WHO, 2022a).

SSFs are typically used for higher quality surface water sources (turbidity < 10NTU) where they can be applied as a single treatment step. For moderately or highly turbid surface water, pretreatment (e.g. T.1.1 Roughing filtration or T.1.4 Coagulation/flocculation/sedimentation) is required to avoid rapid

clogging of the filter. Additional disinfection methods (see T.2.1 Chlorination) may be required as a post-treatment step where there is a risk of microbial recontamination and to provide free chlorine residual protection during storage/distribution. Chlorination must not be applied as a pretreatment as it will impede the effectiveness of the chlorine-sensitive biological Schmutzdecke.

Applicability and adequacy

The design of most SSFs is similar to rapid sand filters (see T.1.2 Rapid sand filtration), but the filter bed requires a uniform medium-grain-sized sand (0.2–0.5 mm) that should be clean and free of clay, earth, and organics. It can be produced by washing and sieving local natural sand. The sand layer height should initially be about 1 m so that the supernatant water (water height above the filter bed) will be 0.6–1.2 m.

SSFs do not necessarily require a power supply and can be operated by gravity, though they can be operated by pumping as well. Each filter requires a ripening period that lasts until the removal of bacteria, viruses, and protozoa stabilizes. Filter ripening establishes the biological activity, which takes some days to several weeks. Therefore, it is usually advisable to install multiple filter units in parallel (see operation and maintenance section). In general, low temperatures decrease biological activity and thus decrease treatment efficiency.

Applications typically range from small communities (e.g. two units of 1 m² filtration area) to municipal water treatment plants.

Operation and maintenance

After running for several months, the slow sand filters will gradually become clogged due to the accumulation of organic and inorganic matter as well as the biological growth of microorganisms within the upper layers of the filter. If the filter flow reduces, the Schmutzdecke (1–3 cm) of the filter bed has to be scraped off manually, washed, dried in the sun, and stored. This needs to be repeated several times until the bed layer decreases to 0.3–0.5 m in height, where-in the scrapped material can be returned back to the filter, ideally towards the bottom of the filter bed. Where a number of filter units are installed in parallel, only one unit should be scraped and ripened at the same time to assure good water quality at all times. The filter run time (time between two scrapings) decreases with a higher solid concentration in raw water, algal growth in supernatant water, smaller filter bed sand, and a higher water temperature.

All valves must be routinely inspected and serviced to prevent blocking, and any leakage in the system must be repaired immediately.

- May require community engagement/ awareness raising on the health benefits of drinking SSF-treated water
- Does not remove inorganic chemical pollutants without specialized design
- Requires time for ripening and the development of the Schmutzdecke to establish the biological activity for optimal treatment efficiency

→ References and further reading materials can be found on page 215.

Health and environmental aspects/Acceptance

Given the filter bed surface is green and slimy, it can be challenging for consumers to accept that the treated water is safe for consumption. Effective communication and consumer engagement is needed to manage such concerns to assure consumers regarding the health benefits of drinking slow sand filter-treated water.

⊕ Advantages

- Does not require the use of chemicals
- Can be constructed with local resources
- Does not require pump/power supply if constructed with gravity flow only
- Has low life-cycle costs (especially low operational costs)
- Simple to operate and maintain
- Can have a long lifespan (> 10 years)
- Improves biological stability of water

⊖ Disadvantages

- Requires large area
- Requires good quality raw water; can be clogged easily if not operated optimally, or where there is excessive turbidity/solids, or algae in the inflow
- Treatment efficiency decreases at low temperatures or if there are rapid changes in raw water quality (including shock chemical loads)
- Does not provide residual protection; requires safe distribution and storage and/or the addition of chlorine post treatment

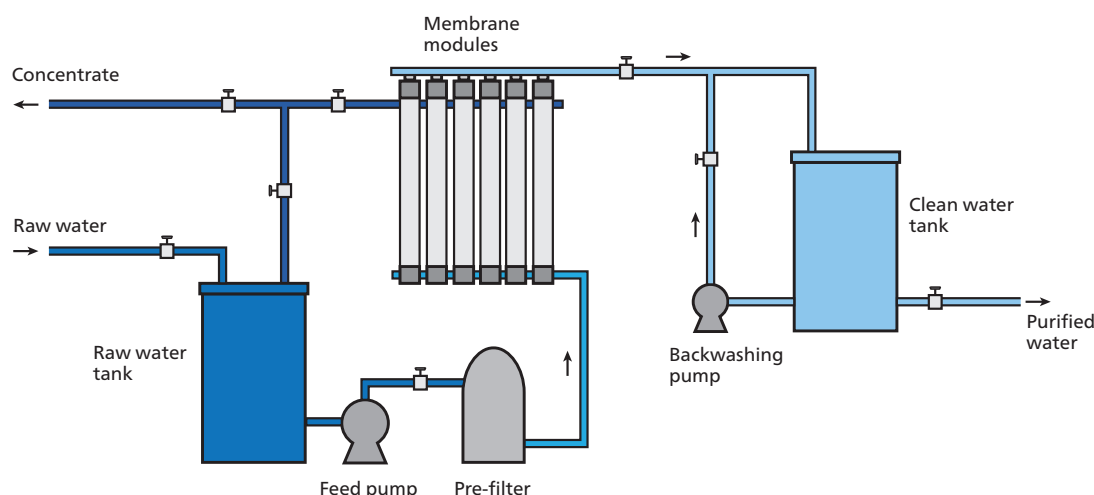
T.2.5 Ultrafiltration

Applicable to systems
2, 3, 6, 7

Management level
Community, centralized

Local availability of technology or components
Setting specific, membrane modules may only be regionally available

Technology maturity level
Established technology



Ultrafiltration (UF) can retain bacteria, protozoa, and most viruses as well as particles and some organic matter. The pressure difference between the inflow (feed) and filtrate (permeate) drives the water through a membrane with small pores and thus removes particles larger than the pore size of the membrane.

The typical UF system includes a feed pump that creates the pressure to filter water through a series of membrane modules placed in racks and connected in parallel. Water is pumped in a dead-end mode wherein all inlet water passes through the membrane. Cross-flow systems also exist that are characterized by a lower recovery and higher energy demand values, and as such, are less common. Typically, UF systems are designed in a modular way, and the capacity of the system can be easily adapted as needed.

The membranes of UF systems are classified by their pore size, with all particles larger in diameter than the pore size retained by the membrane. These pore sizes generally range from 0.01–0.1 μm and can remove turbidity, larger particles, bacteria, protozoa, and most viruses. Often UF membranes are classified by membrane cut-off values in kilodaltons (kDa), which represent the ability of the membrane to retain certain organic polymers of a defined size (e.g. dextran).

The retained particles and microbes accumulate on the membrane surface or in the membrane pores, forming a cake layer. Smaller particles and dissolved organic matter can penetrate into the membrane

pores and adsorb there. Both processes reduce the flow of water through the membrane in systems operated under constant pressure or increase the transmembrane pressure in systems operated using constant flow. The formation of the cake layer and deposition of organic matter within the pores of the membrane is called membrane fouling. Therefore, UF systems need a frequent cleaning by backflushing and/or chemical treatment (see operation and maintenance).

Most commercial UF membranes are polymeric, but ceramic UF membranes are also available. Three major types of membrane modules are used: hollow fiber, spiral wound, and flat sheet. In drinking-water production, mostly hollow fiber modules are used, since they are the most compact, low cost, and consume less energy than other module configurations.

Tight UF membranes run optimally show a high retention of microorganisms, achieving up to 6 log reduction value (LRV) for bacteria, viruses and protozoa (including cysts), with performance varying depending on the integrity of filter medium and filter seals, resistance to chemical and biological ("growth-through") degradation, and general operation and maintenance conditions (WHO, 2017a). Compared to MF membranes, UF membranes remove the same amount of turbidity and suspended solids, while also removing more organic matter. However, the flowrate of UF systems is lower than MF systems at the same operational pressure, which is usually about 0.5–5 bar. The permeability of standard UF membranes varies between 400–1000 L/h/m²/bar.

Applicability and adequacy

Ultrafiltration is an advanced and reliable process for removing microbial contamination. Due to small space requirements, modular designs, and the low need for chemicals, it is suitable for applications at different scales. However, it requires a high degree of automation and process control for the pumps, back-flushing, and system performance. Additionally, investment costs are usually higher than alternative systems, and some level of expertise provided by the operator or supplier is required to maintain the systems. Gravity-driven UF systems exist for small-scale applications in community water supplies.

When selecting a membrane system for disinfection, one should pay special attention to virus removal. MS2 (~0.02 µm) or phi X174 (~0.03 µm) are common viruses used for membrane testing (due to their small size), and in effective membranes, they should achieve at least 3 LRV. Otherwise, an additional disinfection step like T.2.1 Chlorination or T.2.3 Ultraviolet (UV) light disinfection is required.

Operation and maintenance

Depending on the quality of the raw water, the membranes need to be backwashed every 0.5–10 minutes using a backwash pump. Chlorine may be added to reduce the risk of biofouling. Chemical cleaning is required when the fouling occurs to the extent that it cannot be removed by backwashing alone, which is indicated by the system operating at pressure or flow values outside of its optimal design range. Usually, UF is used a single step process, but in-line coagulation can be used as a pretreatment step when high turbidity peaks occur in raw water.

Health and environmental aspects/Acceptance

The waste stream produced during backwashing (retentate) must be disposed of appropriately, given that it contains the concentrated contaminants found in the feed water. Depending on the constituents and the prevailing local health and environmental regulations, disposal options for the retentate may include disposal in the municipal sewer or returning to the head of the water treatment plant. Cleaning chemicals can be corrosive and require trained operators and personal protective equipment.

- Uses a smaller land area for a treatment plant due to transportable and mobile membrane units, in comparison with conventional filtration systems

⊖ Disadvantages

- Requires relatively high investment costs, considerable operational and maintenance costs
- Requires skilled personnel
- Requires reliable energy supply for the continuous operation required to guarantee optimal membrane performance
- Does not provide residual protection; requires safe distribution and storage and/or the addition of chlorine post treatment

→ References and further reading materials can be found on page 215.

⊕ Advantages

- Removes turbidity effectively
- Provides a barrier to bacteria, viruses (has to be verified), and protozoan cysts
- Reduces organics and colour
- Operates constantly and reliably through automation
- Treats water of variable quality

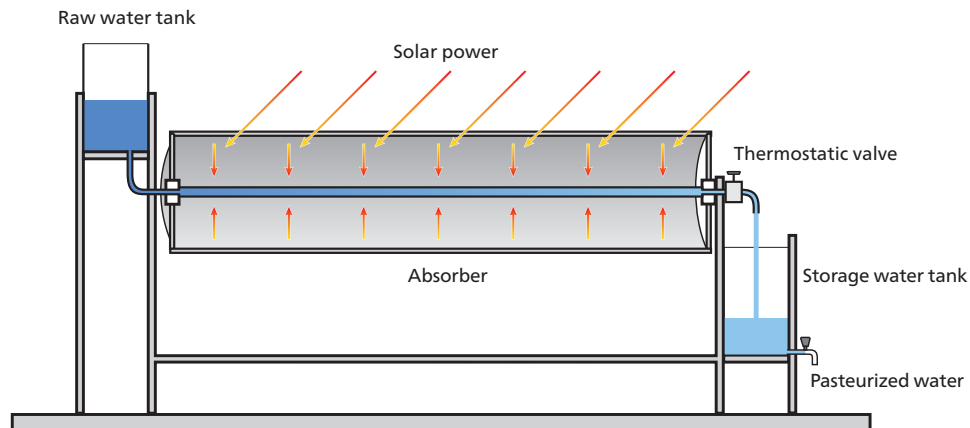
T.2.6 Pasteurization

Applicable to systems
2, 3, 6, 7

Management level
Neighborhood, community

Local availability of technology or components
Setting specific, some key parts may only be regionally available

Technology maturity level
Established technology



Water pasteurization uses heat to inactivate pathogenic microorganisms. Most bacteria, viruses, and protozoa are inactivated at temperatures between 60–70 °C at an exposure time of at least 1 minute. Some bacterial spores and protozoan cysts require longer exposure times, though, so it is recommended to hold 70°C for 15 minutes in practice.

Pasteurization can use any source of heat, including fuel and an open fire, waste heat, and solar power. A heat exchanger is required to use the heat, the design of which depends on the type of heat source.

For neighborhood and community-scale applications, pasteurization can be carried out using solar flow-through systems (for household applications, see H.6 Pasteurization). For a solar flow-through or semi-continuous pasteurization system (see figure above), water stored in a tank flows through a solar collector. At the end of the system, a thermostatic valve is installed. It opens only when the correct water temperature is reached, allowing pasteurized water to flow into the clean water storage container. Once empty, the system is refilled from the raw water tank. This causes the water temperature to drop, and the thermostatic valve closes again. The raw water tank is sometimes filled with gravel or sand for the pre-clarification of the water. For flame- or waste-heat-based systems, a metal tube and a heat exchanger are needed, and the thermostatic valve again regulates the release of water once it has reached the required temperature.

Pathogenic microorganisms are sensitive to heat. For vegetative cells of pathogenic bacteria, viruses, and protozoa, high log reduction values (LRVs) can be achieved at 60–70°C during exposure times of less than 1 minute. However, bacterial spores and protozoan cysts, representing early stages in the life-cycle of some microorganisms, can be more resistant to thermal inactivation. To significantly reduce spores, a sufficient temperature and time must be ensured. Usually, a temperature of 70°C for at least 15 minutes is recommended.

Applicability and adequacy

Semi-continuous (flow-through) units can provide more than 1000 litres per day for a throughput that can supply small communities. These systems require only a slight hydrostatic pressure for operation, which can be reached by elevating a raw water tank that is filled either by pumping or gravity flow when the necessary slope is available. Small-scale systems are relatively easy to operate and only require basic training and some basic plumbing skills. Treated water does not have residual protection from microbial regrowth and recontamination, and should therefore be distributed and stored safely.

Operation and maintenance

The small-scale systems that supply communities need relatively little operation and maintenance. Cleaning the reflecting surfaces regularly is needed for solar pasteurization devices and often should be done on a daily basis. Scratching the surface using

abrasive cleaning materials should be avoided. For installing and maintaining the piping, basic plumbing skills are required. Maintenance and regular control of the thermostatic valve is required to avoid blockage and damage of the system due to the overheating/overcooking of water.

For solar systems, due to the comparably low output and high vulnerability to cloudy weather, operators are advised to supply sufficient redundancy, including excess treatment capacity, alternative treatments, excess storage capacity, and good planning.

Health and environmental aspects/Acceptance

The hot surfaces pose a risk to users through burn injuries. Additionally, concerns may arise from the lack of residual disinfectant. Hence, treated water should be distributed (constant overpressure in the distribution networks and maintenance of a free chlorine residual) and stored safely (see D.4 Small public and community distribution system, D.6 Storage tanks or reservoirs, H.1 Storage tanks or reservoirs). Users might not like the taste of warm water, so cooling the water naturally might increase acceptance (avoid adding ice). Cooling should be done in safe water storage containers to reduce the recontamination risk (see H.1 Storage tanks or reservoirs).

⊕ Advantages

- Has low treatment costs
- Works with different energy sources
- Does not form disinfection by-products

⊖ Disadvantages

- Has a limited treatment capacity and is best suited to small-scale systems
- Provides unpleasant, warm water after treatment until cooled
- Is vulnerable to unstable weather (if solar powered); clouds, rain, and polar regions limit efficiency
- Requires safe distribution and storage due to lack of residual disinfection
- Does not remove turbidity, chemical pollutants, taste, and colour
- Requires pre-clarification for poorer quality water

→ References and further reading materials can be found on page 215.

T.3.1 Fluoride removal methods

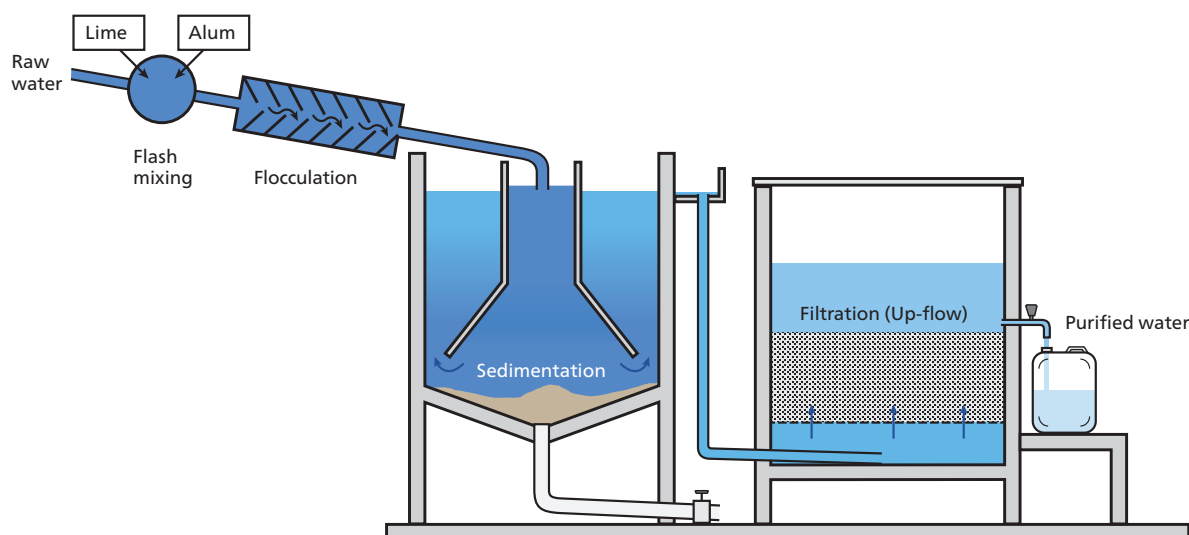
Applicable to systems
6

Management level
Community, centralized

Local availability of technology
or components
Yes, in most settings

Technology maturity level
Established technology

NALGONDA TECHNOLOGY APPLIED ON COMMUNITY SCALE



Fluoride is a groundwater contaminant from geogenic sources, such as minerals in rocks and soils.¹² Fluoride can be removed by adsorption onto calcium phosphate or aluminum-oxide-based filter materials or by precipitation and coagulation treatment processes.

Because fluoride is an essential building block for the formation of tooth enamel and bones, municipal drinking-water supplies in some regions are artificially fluoridated. However, fluoride is also found as a groundwater contaminant from mineral and rocks, and the fluoride levels resulting from this can be significantly higher than the guideline value. The WHO guideline value for fluoride in drinking-water is 1.5 mg/L (WHO, 2022a). The consumption of drinking-water with fluoride levels above this value over a long period of time may lead to the degradation of teeth and bones (i.e. dental and skeletal fluorosis). To counter this, the removal of fluoride from groundwater is possible at household level (see H.10 Fluoride removal filters), at small-scale community sources, and at large drinking-water supplies.

A variety of advanced removal technologies exist, such as T.5.2 Reverse osmosis, or T.5.1 Membrane distillation. The choice of technology depends on the local situation, particularly the available funds, the fluoride concentration in the input water, operation and main-

tenance requirements, the availability of raw materials, and the acceptance of the technology by the population. In low-income countries, low-cost methods rely on precipitation and coagulation or adsorption/ion-exchange processes.

Precipitation/coagulation: The addition of chemicals such as calcium and aluminum salts can form precipitates that bind fluoride and that can be removed by conventional sedimentation and filtration steps. The Nalgonda technique (see figure above) is a well-established method used on a community scale. The coagulants added are aluminum sulphate (alum) and calcium hydroxide (lime). Other techniques include electrocoagulation and the Nakuru technique, the latter being a mixture of precipitation and adsorption processes.

Adsorption and ion-exchange: Fluoride-contaminated water is passed through a layer of porous material (contact bed) that removes fluoride by ion exchange or adsorption to the contact bed material. Appropriate contact bed materials include activated alumina or calcium-phosphate-based materials such as synthetic hydroxyapatite and bone char. An important advantage of adsorption is that many filter materials can be regenerated. When the uptake capacity of the filter is reached, fluoride is removed by passing a basic solution over the filter bed, followed by an acidic solution for reactivation. The filter media can then be reused for further fluoride removal.

Applicability and adequacy

Precipitation/coagulation methods require the daily addition of chemicals to the treatment process and produce sludge every day, which then has to be disposed of appropriately. The main advantages are the moderate treatment costs and the local availability of chemicals. The dosing of chemicals varies according to the groundwater fluoride concentration and needs to be calculated to avoid under/over-dosing.

Activated alumina can also be very effective in removing fluoride and arsenic (see T.3.2 Arsenic removal methods and H.10 Fluoride removal filters) but is not always locally available or may be too expensive. The use of bone char requires frequent monitoring of the fluoride removal, since bone char quality can vary considerably. Synthetic hydroxyapatite (HAP), chemically the same material as bone char, generally has a higher uptake capacity and less fluctuation in quality. For all adsorption processes, the contact bed will become saturated with time and needs to be regenerated or exchanged. The fluoride removal capacity of the filter media generally decreases after each regeneration cycle.

Operation and maintenance

Depending on the type of treatment system, different operation and maintenance activities have to be performed, which are outlined in the *Geogenic contamination handbook* (EAWAG, 2015). In most technologies, the operation and maintenance requirements are significant, including the daily dosing of chemicals as well as sludge removal for coagulation/precipitation processes, and the plant often needs a power supply. For adsorption/ion exchange, the operation and maintenance is less frequent, but when required, it involves regenerating the contact bed using alkalis and acids. These chemicals need to be stored and handled carefully, so this tends to be more suited to the centralized level.

Health and environmental aspects/Acceptance

Bone char may not be acceptable in some areas for religious or cultural reasons. The sludge produced during precipitation/coagulation may be an environmental hazard and needs to be disposed of safely and in line with local health and environmental requirements, as does saturated filter material and regenerant solutions, if used. When ion exchange resins are used, the raw water quality needs to be carefully considered. Other ions with a stronger affinity for the resin can displace fluoride, leading to the uncontrolled release of large quantities of fluoride into treated water.

Nalgonda technology:

⊕ Advantages

- Uses readily available chemicals
- Moderate operational costs

⊖ Disadvantages

- Requires significant labor
- Has only moderate fluoride adsorption capacity
- Produces large amounts of waste

Activated alumina:

⊕ Advantages

- Has high fluoride uptake capacity
- Uses regeneratable filter material

⊖ Disadvantages

- Requires skilled operator for plant operation and regeneration of activated alumina
- Requires expensive filter material

Bone char:

⊕ Advantages

- Uses locally available and low-cost materials
- Requires only short contact time

⊖ Disadvantages

- Requires experience and investments for production infrastructure (e.g. kiln)
- Can be of variable quality
- Requires frequent contact bed material replacement due to low to moderate fluoride uptake capacity

Membranes:

⊕ Advantages

- Removes other chemical contaminants and pathogens

⊖ Disadvantages

- Is complex and maintenance-intensive
- Requires expensive technology

→ References and further reading materials can be found on page 215.

¹² See risk maps showing regions with a high likelihood of elevated fluoride concentration in groundwater: <https://www.gapmaps.info>

T.3.2 Arsenic removal methods

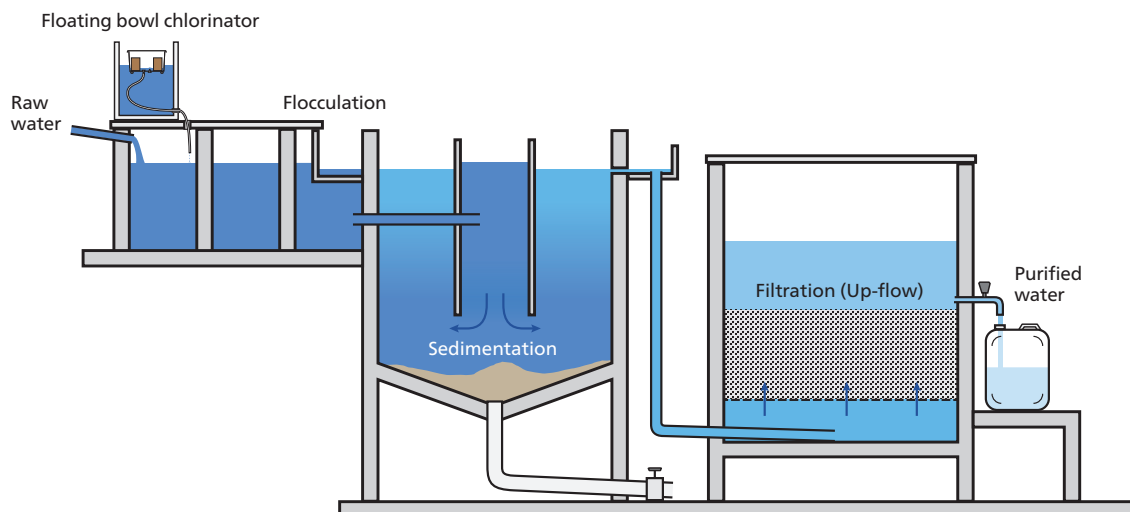
Applicable to systems
6

Management level
Community, centralized

Local availability of technology
or components
Yes, in most settings

Technology maturity level
Established technology

ARSENIC REMOVAL USING A CONVENTIONAL COAGULATION BASE TREATMENT UNIT



Arsenic is a groundwater contaminant that originates from geogenic sources, such as natural minerals. Arsenic is conventionally removed from groundwater by precipitation, adsorption, and ion exchange processes.

Several regions of the world are severely affected by arsenic in groundwater,¹³ which can be derived from natural sources, such as rocks and soil, as well as from industrial activities like mining. The consumption of arsenic-contaminated water over a long period can result in chronic arsenic poisoning. Long-term exposure to arsenic changes the skin pigmentation and increases the risks of various lung and heart diseases. The WHO guideline value for arsenic in drinking-water is 10 µg/L, which is provisional on the basis of the difficulties with removing arsenic to lower levels using conventional water treatment (WHO, 2022a). When resources are available, every effort should be made to keep concentrations as low as reasonably possible and below the guideline value. In settings where arsenic occurs above this value, the public health priority should be to reduce exposure. Governments may set higher limits or interim values as part of an overall strategy to progressively reduce risks, while considering local circumstances, available resources, and risks from low arsenic sources that are microbiologically contaminated. Where appropriate, mitigation strategies, such as the use of alternative water sources or blending (mixing different sources), should be considered.

In the environment, arsenic occurs in the form of trivalent arsenic, (arsenite, [As(III)]) and pentavalent arsenic (arsenate [As(V)]), where the prevailing form depends mainly on the redox conditions. In groundwater, trivalent arsenic is common, which is more difficult to remove than pentavalent arsenic. Pentavalent arsenic strongly sorbs to various solids, such as trivalent iron oxides and hydroxides. Therefore, a pre-oxidation step of trivalent arsenic by ozone or various chemicals is recommended to form pentavalent arsenic prior to water treatment.

Arsenic removal is possible at the household level (see H.11 Arsenic removal filters) as well as at community scale. Similar to fluoride removal, methods for arsenic removal include precipitation/coagulation, adsorption (see T.4.1 Activated carbon), ion exchange (see T.3.1 Fluoride removal methods), and reverse osmosis processes (see T.5.2 Reverse osmosis). In centralized water treatment systems, conventional precipitation/coagulation and adsorption (adsorption co-precipitation) methods are usually applied. Iron [Fe(III)] or aluminum [Al(III)] salts are added as a coagulant, followed by sedimentation of the formed flocs and rapid sand filtration.

Applicability and adequacy

Precipitation/coagulation methods require the daily addition of chemicals to the treatment process, and produce sludge every day, which has to be disposed of appropriately. The main advantages lie in the moderate treatment costs and the local availability of

chemicals. The chemical dosing varies according to the arsenic concentration and needs to be calculated to avoid over/under dosing. The conventional coagulation processes cannot always efficiently remove arsenic to very low levels (below 10 µg/L), but to reduce the risk, it should at least be removed to below 50 µg/L. Iron-based methods are effective for pentavalent arsenic, but are less effective for trivalent arsenic unless it is pre-oxidized. Activated alumina and reverse osmosis are very effective in removing arsenic, but the technologies are expensive and not always locally available.

Operation and maintenance

Depending on the type of treatment system, different operation and maintenance activities have to be performed, which are outlined in the *Geogenic contamination handbook* (EAWAG, 2015). For coagulation/precipitation processes, the operation and maintenance includes the daily dosing of chemicals as well as sludge removal, and the plant often needs a power supply. For ion exchange resins, operation and maintenance is less frequent, and when required (e.g. after several hundred to thousand filtered bed volumes), it is a fairly easy process typically involving regenerating the contact bed using a concentrated salt (NaCl) solution. For activated alumina, regenerating the contact bed is done using a strong alkali followed by a strong acid. These chemicals need to be stored and handled carefully, so this tends to be more suited to the centralized level.

Health and environmental aspects/Acceptance

Highly toxic arsenic-rich waste is produced by most of the arsenic removal processes and has to be disposed of safely and in line with local health and environmental requirements. When ion exchange resins are used, the raw water quality needs to be carefully considered. Other ions with a stronger affinity for the resin (sulfates, phosphates) can displace pentavalent arsenic, leading to the uncontrolled release of large quantities of arsenic into the treated water.

Conventional precipitation and coagulation:

⊕ Advantages

- Moderate operational costs
- Uses chemicals that are often locally available

⊖ Disadvantages

- Requires pre-oxidation
- Generates toxic sludge
- Requires time consuming operation and maintenance

Iron-based solids:

⊕ Advantages

- Effectively removes pentavalent arsenic [As(V)]; acceptable removal of trivalent arsenic [As(III)]
- Is available commercially

⊖ Disadvantages

- Is moderately expensive
- Produces arsenic-rich waste

Activated alumina:

⊕ Advantages

- Has high arsenic removal efficiency
- Is commercially available

⊖ Disadvantages

- Is moderately expensive
- Requires difficult regeneration

Ion exchange resins:

⊕ Advantages

- Has high arsenic adsorption
- Is commercially available

⊖ Disadvantages

- Is moderately expensive
- Experiences interference from sulfate and total dissolved solids (competing ions)

Membrane systems (i.e. reverse osmosis):

⊕ Advantages

- Removes other chemical contaminants and pathogens

⊖ Disadvantages

- Is complex and maintenance-intensive
- Requires expensive technology

→ References and further reading materials can be found on pages 215 and 216.

¹³ See risk maps showing regions with a high likelihood of elevated arsenic concentration in groundwater: <https://www.gapmaps.info>

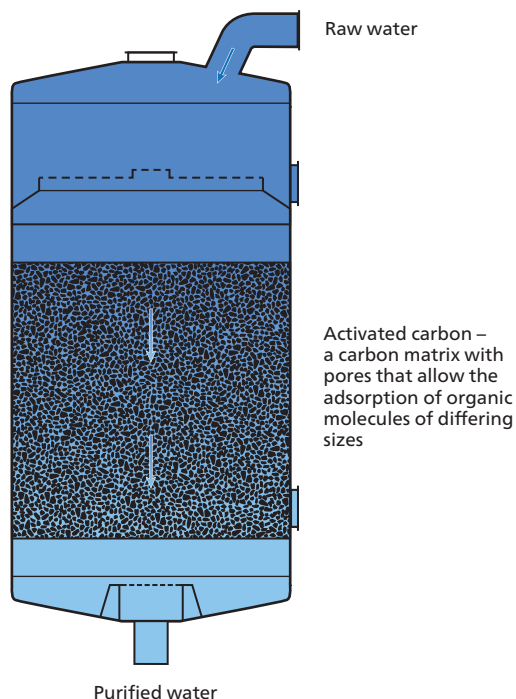
T.4.1 Activated carbon

Applicable to systems
7

Management level
Household, community,
centralized

Local availability of technology
or components
Yes

Technology maturity level
Established technology



Activated carbon (AC) is the most commonly used adsorption method in drinking-water to remove taste-, odour-, and colour-causing compounds; natural organic matter; disinfection by-products; and synthetic organic chemicals present in the source water. In small-scale installations, it is often used for chlorine and chloramine removal, as well. Activated carbon can also be used for biological water treatment, such as post-treatment after ozonation, as it provides a high surface for microbial growth.

Made from organic materials that have a high carbon content (e.g. coal, wood, coconut shells, peat, or lignite), AC is characterized by a highly porous structure that provides a large surface area of 500–2000 m²/g for effective adsorption of target contaminants. Adsorption consists of molecules and to some degree particles attaching at the interface between a liquid (e.g. water) and a solid phase (e.g. activated carbon).

For drinking-water treatment, AC is applied in different forms, such as powdered, extruded, and granular carbon, depending on the size of the plant, treatment objective, and convenience for the specific circumstances. The main difference between the different forms of carbon is the particle size, which ranges between 0.3–2.5 mm (8–50 mesh) for granular activated carbon (GAC). GAC is the most common type used in

small-scale systems and is normally applied in a fixed-bed adsorber (GAC filter) that filters the feed water and retains the target compounds by adsorption. The main design parameters involve the flow rate, usually ranging between 5–15 m/h, and the empty bed contact time (EBCT), which is calculated by dividing the filter bed volume by the flow rate. EBCT typically ranges between 5–30 minutes in drinking-water treatment, while the actual duration of contact between the water and the filtration medium is approximately one third of the EBCT, i.e. 2–10 minutes.

Applicability and adequacy

Activated carbon filters can only treat feed water that is relatively low in turbidity. Particle-rich, highly turbid water requires pretreatment to avoid a pressure loss due to rapidly clogging the activated carbon. Feed water with a high concentration of background organic matter, e.g. humic substances, will rapidly exhaust the adsorption capacity.

Activated carbons vary significantly in their capacity to retain specific organic compounds, which can lead to the early breakthrough of poorly adsorbable pollutants while the readily adsorbable organics are still efficiently adsorbed. The carbon type and material are thus selected according to the water quality objectives.

When the GAC is not replaced and the removal capacity has been reached, the GAC can still influence

the water quality. The large surface area of GAC provides favorable conditions for biofilm development, which provides some removal of certain biodegradable organic compounds in drinking-water. Thus, the biological stability of the treated water (the resistance to microorganism regrowth) increases, reducing the risk of biological regrowth in distribution networks.

→ References and further reading materials can be found on page 216.

Operation and maintenance

During filtration, the activated carbon filter becomes continuously loaded with contaminants, such as organic compounds, until the capacity of the filter is exhausted. At this breakthrough point, the activated carbon has to be replaced by fresh carbon or a new filter element. In most drinking-water applications, the service life of carbon filters is in the range of months (typically 6–12 months) but can be significantly reduced if overloaded. Exhausted AC can be reactivated by the carbon supplier by burning off the organics at a high temperature.

The tendency for GAC filters running for several months to grow a biofilm can lead to pressure loss due to microbial growth. GAC filters should therefore be regularly backwashed. If the GAC filters are not replaced as required, the GAC does not adsorb sufficient organic pollutants.

Health and environmental aspects/Acceptance

AC is a widely applied and accepted technology. To ensure safe water quality, AC treatment should be followed by a final disinfection stage.

Loaded carbon requires appropriate treatment. GAC should be regenerated when required. Filter breakthrough must be avoided, as this can release contaminants from the filter media in concentrations higher than the source water due to contaminant accumulation in the AC filter media.

⊕ Advantages

- Removes taste and odour, chlorine, and organic contaminants
- Is low maintenance
- Adapts to many designs and target compounds
- Filter elements and carbon blocks have simple replacement

⊖ Disadvantages

- Loses performance rapidly if treating source waters with high turbidity or background organics
- Removes microbial contaminants poorly
- Requires regular replacement of GAC, often at high cost

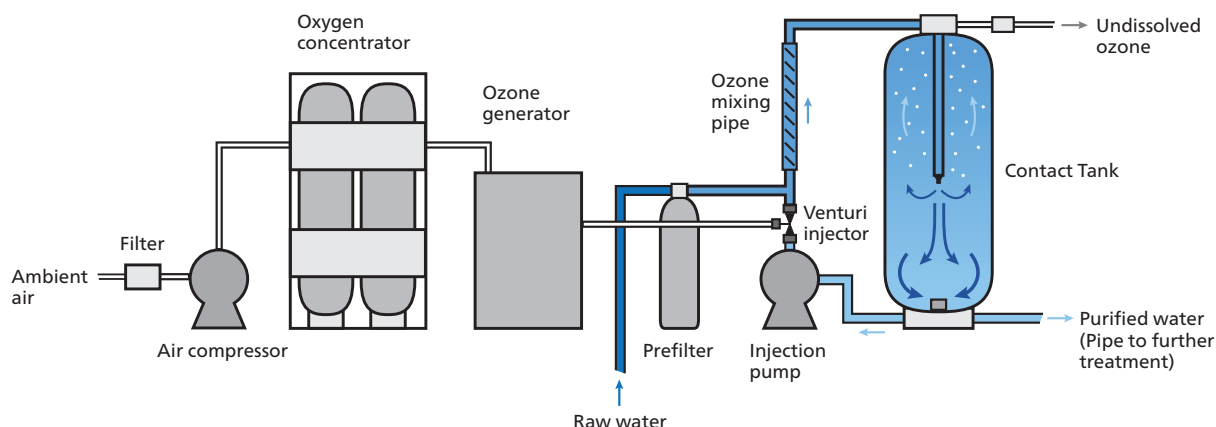
T.4.2 Ozonation

Applicable to systems
7

Management level
Centralized

Local availability of technology
or components
Setting specific, some key parts may
only be regionally available

Technology maturity level
Established technology



Ozone gas effectively degrades a wide range of water contaminants, including organic and inorganic compounds, and inactivates bacteria, viruses, and some protozoa. Ozone has to be produced at the treatment facility with on-site generators, which require a reliable power supply.

The ozone gas molecule consists of three oxygen atoms (O_3). It is highly unstable and reactive toward a wide variety of water contaminants, such as inorganic (e.g. iron, manganese) and organic compounds (including micropollutants such as organic pesticides) as well as microorganisms and their metabolites (e.g. cyanobacterial toxins and taste- and odour-causing compounds). Ozone attacks contaminants either directly or indirectly through its decomposition in water to form hydroxyl radicals ($OH\cdot$). The $OH\cdot$ radical reacts rapidly with a large number of drinking-water contaminants.

The most common generators produce ozone (O_3) by subjecting oxygen (O_2) or air to a high electric voltage (Corona discharge-type generators) or to UV radiation (UV-type generators). Corona discharge-type generators are applied for large-scale applications producing ozone concentrations of 1–4.5% by weight. UV-type generators achieve ozone concentrations of 0.1–0.001% by weight and are used for treating smaller quantities of water. Ozone gas is transferred to the raw water via fine bubble diffusion or side-stream injection. In the contact tank, ozone reacts with water contaminants, requiring only a short contact time (approximately 10–30 minutes). An off-gas system destroys any undissolved ozone.

Ozone rapidly decomposes in water, which makes its lifespan very short (less than one hour). Thus, it is not suitable as a residual disinfectant that protects the drinking-water distribution system from regrowth/recontamination. Ozonation and chlorination (T.2.1 Chlorination) can therefore be used in tandem to inactivate a wide range of microorganisms at the treatment plant and to protect the water during distribution/storage.

Applicability and adequacy

Ozone can be added at several points in the drinking-water treatment system: at the beginning of the treatment (pre-ozonation), after sedimentation and before filtration (intermediate ozonation), or as final disinfection step.

As a pretreatment oxidant, it is added early in the treatment process to react with contaminants, including iron, manganese, and sulfur; micropollutants; and colour-, taste- and odour-causing compounds. After ozonation, the removal of degraded compounds is improved in subsequent treatment steps, such as sedimentation or filtration (see T.1.4 Coagulation/flocculation/sedimentation and T.1.5 Coagulation/flocculation/filtration), including sand (see T.2.4 Slow sand filtration) and GAC filters (see T.4.1 Activated carbon). In low turbidity water, ozone treatment forms colloids (micellization process). Adding a small quantity of coagulant transforms the colloids into micro-flocs, which are easily retained by sand filters (see T.2.4 Slow sand filtration). For organic compounds, the required amount of ozone and sub-

sequent ozone decomposition is highly dependent on the quantity and types of contaminants targeted. As a rule of thumb, the initial ozone demand is 2.5 mg ozone/mg of chemical oxygen demand (COD).

Ozone can also inactivate microbial pathogens in water and is effective against bacteria, viruses, and some protozoa. Unlike chlorine, ozone is effective across a wide pH range. Information on ozone concentrations and contact times (Ct values) for the inactivation of microorganisms can be found in LeChevallier & Au (2004).

Operation and maintenance

The design, construction, operation, and maintenance of ozonation systems need skilled staff. The high-tech equipment is costly and has a comparably high power demand.

Ozone systems occasionally develop ozone leaks, requiring an ambient ozone monitor as well as regular checks of the generator and contact tank. Further operations and maintenance works include: i) maintaining the required flow of generator coolant to mitigate system overheating, ii) regularly inspecting and cleaning the ozone generator, feed gas supply, and electrical assemblies, iii) monitoring the ozone gas-feed and distribution system to ensure that the necessary volume of ozone comes into sufficient contact with the raw water.

Health and environmental aspects/Acceptance

The ozonation of bromide-containing waters can form bromate, a known carcinogen, with a WHO provisional guideline value of 10 µg/L in drinking-water (WHO, 2022a). Techniques to control bromate formation involve ozonation at slightly acidic pH values, multi-stage ozonation, and the use of ammonia or chlorine. Once bromate is formed, GAC filters (see T.4.1 Activated carbon) and UV light disinfection (see T.2.3 Ultraviolet (UV) light disinfection) can remove it to a limited degree. Ozone gas is possibly toxic and extremely irritating to the human body, so leaks must be controlled to prevent worker exposure.

⊖ Disadvantages

- Requires skilled staff for operation and maintenance
- Has high equipment, operation, and energy costs
- Does not provide residual disinfection
- Requires careful monitoring of ambient ozone levels
- Forms the carcinogenic by-product bromate if bromide-containing water is treated. Formaldehyde may also be formed as a by-product

→ References and further reading materials can be found on page 216.

⊕ Advantages

- Eliminates a wide variety of inorganic (iron, manganese, sulfur) and organic contaminants (micropollutants) as well as colour-, taste- and odour-causing compounds
- Effectively inactivates bacteria, viruses, and some protozoa over a wide pH range
- Ozonation by-products are generally removable by subsequent filtration step

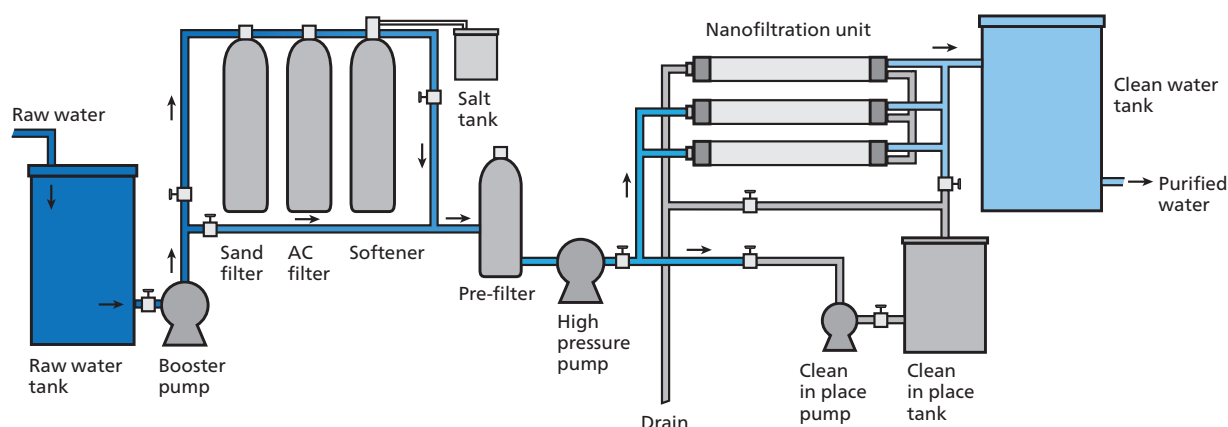
T.4.3 Nanofiltration

Applicable to systems
7, 8

Management level
Community, centralized

Local availability of technology or components
Setting specific, membrane modules may only be regionally available

Technology maturity level
Established technology



Nanofiltration (NF) membranes have pore sizes ranging between 0.001–0.01 μm , which allow water molecules to pass through while retaining the majority of the chemical and microbial contaminants. The membranes may allow small uncharged organic compounds and monovalent ions to pass through to a lesser degree.

Nanofiltration uses tight (dense) polymeric membranes that provide a physical barrier to almost all contaminants of concern. Traditionally employed in desalination (see T.5.2 Reverse osmosis), the membranes have gained increasing interest for the removal of organic chemicals often present in traces in source water due to anthropogenic pollution.

Depending on the type of membrane, the produced permeate consists mainly of water with a very low residual salinity. These permeates are also softened due to the removal of bivalent ions and other potential scales. The water that does not pass the membrane is called concentrate, and it contains all the retained pollutants such as heavy metals, microbial contaminants, trace organic chemicals, bulk natural organic matter, and to some extent inorganic salts.

Because NF requires an inlet water low in natural organic matter and turbidity, multi-media filtration or ultrafiltration/microfiltration is often applied as a pretreatment to retain particulate and colloidal matter. Typical NF membranes are spiral wound elements, installed in high pressure stainless steel housing and used with high pressure pumps. The NF systems are operated in crossflow mode, where part of the water

is recirculated in the system and is subsequently released as concentrate. The systems run mostly at water recoveries of 80–90% with 10–20% concentrate. The feed water that is “lost” as concentrate increases the specific treatment costs due to disposal and lower purified water volumes. For cost optimization, the concentrate volume and amount of other reject streams should be minimized.

Applicability and adequacy

Nanofiltration can be used to treat waters affected by anthropogenic contamination. The membrane properties, operating pressure, and pretreatment processes in place might impact the rejection rates for inorganic and organic contaminants. Removal for bacteria, viruses, and protozoa usually exceed 6 log reduction value (LRV) in well operated and maintained systems, but varies for different membrane materials, configurations, and study set-ups. The integrity of the membrane modules and the applied manufacturing quality control measures impact the performance considerably.

Nanofiltration is usually applied at a large scale, although there are packaged systems available on the market that integrate the system components and pretreatment in one rack. Nanofiltration requires a pressure of typically around 5–10 bar for operation. Membrane fouling (by inorganic and organic compounds as well as biofouling due to the proliferation of microorganisms on the membrane surface) impacts the membrane permeability, removal performance, and lifetime. Certain membranes are more susceptible to fouling than others, so the impact of water quality

on the performance of different membrane materials and types should be assessed before selecting the appropriate NF membrane. Contrary to ultrafiltration (see T.2.5 Ultrafiltration), NF membranes cannot be backwashed, and chlorine as well as chemical cleaning agents damage the membrane materials. Thus, reliable pretreatment and operational parameters are crucial for good performance, and the lifetime may be limited to 2–5 years.

Due to the high cost, it is not recommended to use NF purely for disinfection purposes. Ideally, water sources that are not polluted by anthropogenic contamination should be considered first whenever possible.

Operation and maintenance

Operation and maintenance are relatively complex and usually involve advanced process/plant automation to control the performance and ensure the unit is operating in the optimum range. These procedures for fully automated systems require experience with the respective system design as well as process automation and online monitoring. Thus, adequate ongoing technical support from the manufacturer (including the possibility of on-site assistance) should be available locally.

To minimize the deposition of calcium and magnesium salts on the membrane surface, anti-scalants (substances binding calcium and magnesium to reduce their precipitation) can be used, which adds to the costs of treated water and contributes to the need for treating the concentrate as wastewater.

Health and environmental aspects/Acceptance

Nanofiltration membrane processes are widely accepted due to their effectiveness over a very broad range of contaminants, but applications are limited due to the high costs. Proper environmentally friendly handling of the reject streams is needed. Used NF membranes are not readily recycled and are typically treated as waste.

- Needs ongoing technical support from the manufacturer (including on-site assistance)
- Removal of viruses dependent on membrane pore size, layer and material

→ References and further reading materials can be found on page 216.

⊕ Advantages

- Can effectively remove microorganisms, suspended particles, colloids, inorganic chemicals, heavy metals, colour, odour
- Removes organic pollutants effectively
- Removes microbial pathogens effectively
- Removes hardness
- Operates fully automatically

⊖ Disadvantages

- Is a highly complex process
- Produces a concentrate that needs to be discharged or treated separately
- Has high operational and maintenance costs

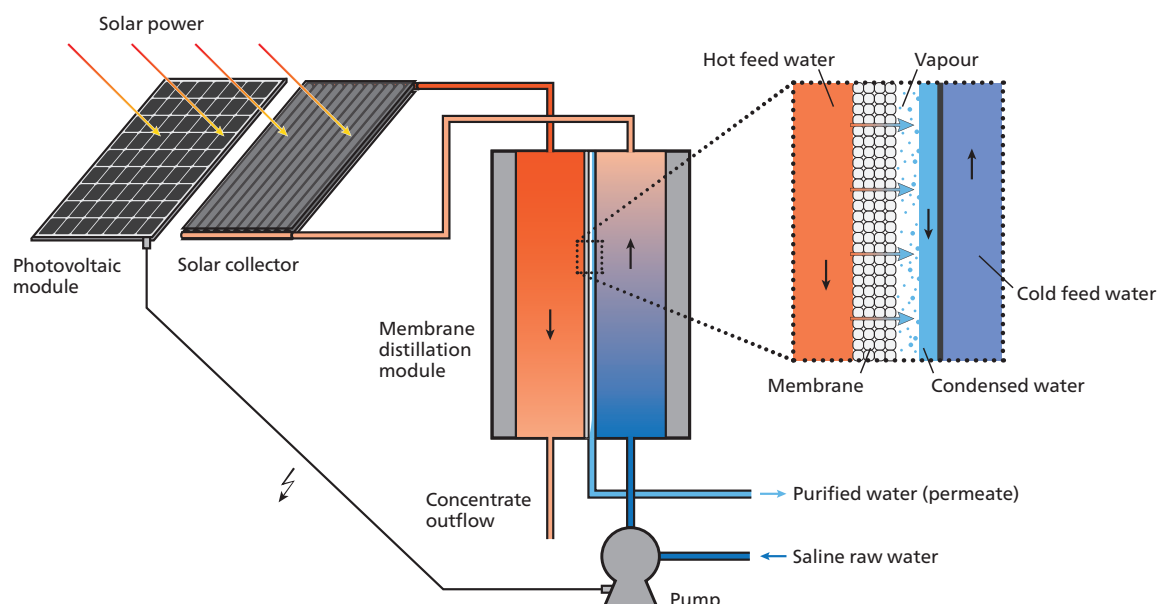
T.5.1 Membrane distillation

Applicable to systems
8, 9

Management level
Community, centralized

Local availability of technology
or components
No

Technology maturity level
Full-scale demonstration



Membrane distillation (MD) is a thermal separation process that combines thermal desalination with membrane technology. The feed water is heated (to around 50–80 °C) and then passes as vapor through a hydrophobic (water repellent) membrane that allows only vapor to cross the pores before it condenses on the permeate (distillate) side.

In MD, the two liquid streams (i.e. the feed water and permeate) remain separated by surface tension while higher vapor pressure on the warmer feed side drives water molecules across the membrane. Relatively low temperature differences of the order of 5–10 °C are sufficient to drive this process. The vapor pressure difference over the membrane is the driving force, which is applied using differing module types and a variety of configurations, such as direct-contact MD or vacuum-enhanced MD.

In seawater desalination, incoming seawater can be used for cooling on the condensate side of the module, and it is preheated before conveying it to the main heat source. This could be done using low grade heat, such as from a diesel generator or solar thermal collectors. In industrial settings, waste heat is also often available that can be used for MD. The heated seawater

is then pumped to the hot side of the membrane distillation module as the feed water.

Applicability and adequacy

Membrane distillation is particularly suitable in locations where low grade heat (< 85 °C) is available to heat the feed water that drives the desalination process. This requires a rather low energy demand of around 1–1.5 kWh/m³ of electric power in addition to the thermal energy required to drive the process.

Desalination coupled with power supplied by a diesel generator can provide an integrated, efficient solution to generate energy as well as water for remote locations with saline or brackish water sources.

The process is relatively complex and requires a sound assessment of the water composition, temperature differences and their variations, and the optimum integration of the system components.

Operation and maintenance

The operation and maintenance are relatively complex and involve advanced process/plant automation to control the performance and operate the unit in the optimum range.

Ongoing technical support from the manufacturer (including on-site assistance) should be available locally

since operating and maintaining the fully fledged automated systems requires experience with the respective system design as well as process automation and online monitoring.

To minimize membrane fouling (deposition of organics and scaling), a good pretreatment, the addition of anti-scalants, and in some cases, biocides are required.

Health and environmental aspects/Acceptance

Membrane distillation might require post-treatment remineralisation to increase the mineral content (including calcium and magnesium) or to adjust the pH to reduce the risk of corrosion.

Used MD modules are not readily recycled and may need to be disposed of as waste. The MD concentrate streams (brine) contain elevated concentrations of contaminants and must be disposed of in line with local health and environmental requirements so as not to impact human and ecological health.

⊕ Advantages

- Produces drinking-water reliably and stably from salt-impacted sources and seawater, particularly suitable for high salinities
- Requires low electric energy inputs

⊖ Disadvantages

- Requires heat source
 - Generates reject stream that requires separate handling or diligent discharge
 - Has limited commercial availability and corresponding technical support
 - Needs ongoing technical support from the manufacturer (including on-site assistance)
-

→ References and further reading materials can be found on page 216.

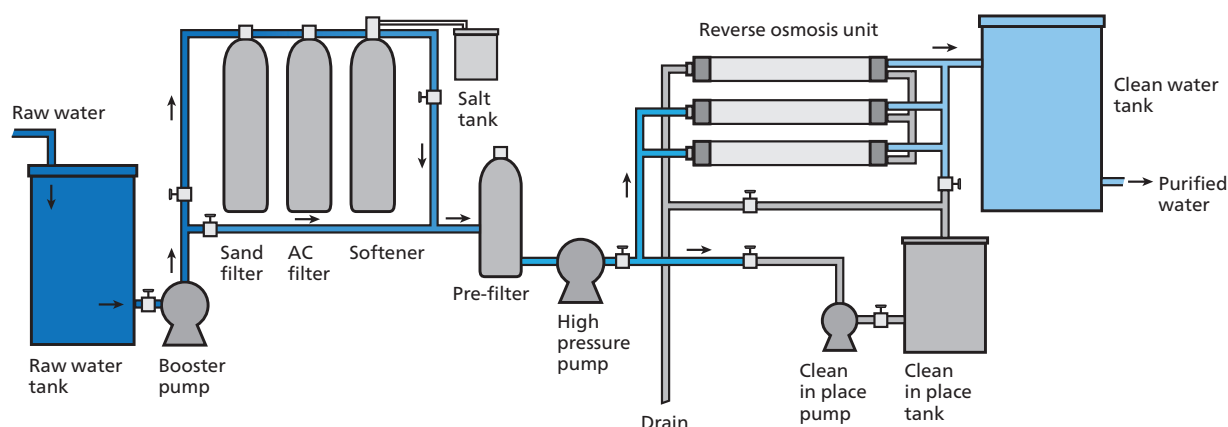
T.5.2 Reverse osmosis

Applicable to systems
7, 8, 9

Management level
Community, centralized

Local availability of technology or components
Setting specific, membrane modules may only be regionally available

Technology maturity level
Established technology



Reverse osmosis (RO) is a pressure-driven membrane process to desalinate (remove salt from) brackish water and seawater as well as to remove various organic and inorganic compounds and microorganisms from drinking-water. The salt rejection reaches up to 99.0–99.5% for brackish water applications and up to 99.8% for seawater.

Reverse osmosis is a state-of-the-art technology for desalinating water resources. In the last decades, significant technological improvements were made in several cost relevant areas, such as energy efficiency and fouling control. However, the energy consumption of RO systems is significantly higher than water treatment from conventional sources, ranging between 2.5–4 kWh/m³ for seawater and 0.4–2.0 kWh/m³ for brackish water.

Reverse osmosis membrane modules are typically designed as spiral wound modules made from flat sheet asymmetric polymeric membranes available in standardized sizes from various manufacturers. The achievable maximum recovery or conversion rate is the percentage of product (permeate) to feed water. This recovery is limited by the membrane properties, feed water composition, salt content, and concentrations of poorly soluble salts. Considering all of these factors helps to safeguard stable operation and prevent scaling (salt deposits), fouling (organics), and biofouling (proliferation of biofilms on membrane surface). Typical recovery rates vary between 70–97% for brackish water desalination and 40–60% for seawater desalination.

Reverse osmosis requires proper system integration in terms of pre- and post-treatment, which often comprises a number of elements. Pretreatment by ultra-filtration or multi-media filtration, for example, controls the organic and particle load entering the RO step. Clean in place (CIP) processes enable significant recovery of membrane performance, which tends to deteriorate over time due to ageing, scaling, and fouling. The addition of anti-scalants might be needed to reduce scaling. Many RO plants run with a constant dosing of chloramines to reduce biofouling, though the addition of stronger oxidants (ozone, chlorine, etc.) destroys the membrane material. A number of pumps, including high pressure pumps to drive the RO process, are required.

RO membranes provide a safe barrier to most contaminants by also removing other critical ionic compounds such as arsenic, fluoride, and nitrate as well as microorganisms. Reverse osmosis can achieve up to 6 log reduction value (LRV) for bacteria, viruses and protozoa. However, performance will depend on the integrity of the filter medium and filter seals, resistance to chemical and biological (“grow-through”) degradation, and general operation and maintenance conditions (WHO, 2017a).

Demineralised water has a low pH and alkalinity, and therefore is corrosive in distribution systems and storage tanks. It might also pose health risks due to dietary mineral deficiency when used as a main source of drinking-water. Therefore, the remineralisation of desalinated water or blending with other water sources is required post treatment.

Applicability and adequacy

System designs must consider the site-specific salinity and ion composition of the raw water, particularly to define the achievable recovery rates and optimum energy usage as well as to avoid the formation of salt deposits (scaling) in the desalination plant.

Desalination powered by solar (photovoltaic or solar thermal) or wind can be reliably operated in remote locations. Though small-scale, fully automated systems and packaged plants exist on the international market, many RO systems are established at a large scale.

Generally, due to high costs and complex maintenance, reliable ongoing technical support from the manufacturer as well as on-site expertise are needed for maintaining RO systems. If other water sources are available that are not affected by anthropogenic contamination or salinity, they should be considered first.

Operation and maintenance

Operation and maintenance are relatively complex and involve advanced process/plant automation to control the performance and operate the unit in the optimum range. The membrane systems are designed by considering the raw water quality and should be operated at a determined flow and recovery rate. When it becomes impossible to maintain the pre-defined parameters, support from a qualified manufacturer's technical support team or an on-site expert is required. In addition, the operation and maintenance procedures of fully automated systems require experience with the respective system design as well as process automation, electronics, and online monitoring.

To minimize membrane fouling (deposition of organics and microbes on the membrane surface), anti-scaling agents (e.g. polyphosphates or polyacrylic acids), biocides (e.g. chloramines), and other chemicals are frequently used. The lifetime of the membranes may reach up to five years before they need replacement.

Health and environmental aspects/Acceptance

Handling of the concentrate is one particular concern in desalination by thermal or membrane processes. During seawater desalination, the concentrate is often discharged to the ocean, which can negatively affect sea life. Brackish water desalination often requires other solutions due the land-locked plant location. For these plants, the concentrate can be discharged as wastewater, evaporated in ponds, further treated towards (costly) zero-liquid discharge, or used for aquaculture or irrigation of halophilic plants.

RO might require post-treatment to increase the mineral content (including calcium and magnesium) or to adjust the pH to reduce the risk of corrosion.

Remineralisation can also be considered, in consultation with public health authorities, where there is a need to increase the overall mineral nutrition of the local population, particularly where drinking-water was previously supplied by groundwater or surface water sources. Essential elements are commonly found in these water sources, although drinking-water typically contributes only a small proportion to the recommended daily intake of essential elements, with food as the main source (WHO, 2009; 2011). Used RO modules are not readily recycled and may need to be disposed of as waste.

⊕ Advantages

- Produces drinking-water reliably and stably from salt-impacted sources
- Is well established and widely applied, with a broad range of suppliers of membranes

⊖ Disadvantages

- Has a relatively high cost and high energy consumption
 - Generates a reject stream that requires separate handling and appropriate discharge
 - Needs ongoing technical support from the manufacturer (including on-site expertise)
-

→ References and further reading materials can be found on pages 217.

This section describes the technologies or solutions used to deliver water from the source, pumping station, or water-treatment plant to the home of the consumer. They are either privately adopted solutions (D.1 Jerry cans–D.3 Water kiosk) or distribution systems with different levels and types of connections (D.4 Small public and community distribution system – D.6 Storage tanks or reservoirs).

D.1 Jerry cans

D.2 Water vendors (carts and trucks)

D.3 Water kiosk

D.4 Small public and community distribution systems

D.5 Centralized distribution systems

D.6 Storage tanks or reservoirs

The choice of the distribution system in any given context depends on the:

- Availability of financial resources
- Quantity of water
- Population density in the supplied area and the distance to the source or treatment plant
- Management considerations
- Availability of service providers
- Topography

D.1 Jerry cans

Applicable to systems
4, 5, 6, 7

Management level
Household

Local availability of technology
or components
Yes

Technology maturity level
Established technology



Jerry cans are light plastic containers that can be carried by one person. They can be sealed with a lid to prevent water contamination and are frequently used to carry water home from the source.

Jerry cans are produced in different sizes, usually ranging from 3 to 30L, with 20L the typical size used by adults to carry drinking-water. Jerry cans can be carried by consumers directly or transported using donkeys or bicycles. They can also be transported and sold pre-filled by water vendors on carts or with cars. Water kiosks or drinking-water companies sometimes sell water in sealed jerry cans or large polyethylene terephthalate (PET) bottles and organize transport to the home.

Applicability and adequacy

Transporting water in jerry cans is a reality for many rural and urban families. Depending on the water source situation, this often requires a lot of time that could be used for other activities. As defined in Human Right to Water (UN General Assembly, 2010), the time spent carrying water should not exceed 30 minutes per day. In areas where water sources are located at longer distances, other water distribution options should be considered. The transport of jerry cans filled with safe water to the home by water kiosk providers can be costly but is a generally adequate option when the water and jerry cans are disinfected and safely sealed.

Operation and maintenance

The frequent cleaning and disinfection of jerry cans is often done using chlorine (e.g. 0.5% hypochlorite solution) to avoid water recontamination with pathogenic microorganisms or the formation of biofilms or precipitates. Abrasive materials can effectively clean jerry cans, though may also damage the internal surface. This provides a greater surface area and niche for microbial growth, which can be more challenging to remove during subsequent rounds of cleaning. When abrasive materials are used, the jerry cans should subsequently be disinfected with a 0.5% hypochlorite solution. Because of the potential for cross contamination, dedicated jerry cans should be reserved especially for drinking-water. Water for other needs or from unsafe sources should not be transported in the same jerry cans. Additionally, jerry cans made from plastics of low quality can become brittle when exposed to sun and heat over longer periods of time. Therefore, jerry cans should not be stored outside in direct sunlight for extended periods.

Health and environmental aspects/Acceptance

Jerry cans can easily become contaminated during water abstraction or storage at home or when used for other unsafe water sources. Recontamination can be reduced by using sealed containers with tightly fitting lids cans and/or by chlorinating the water in the jerry cans. When empty, users should avoid touching the surfaces of the jerry cans and reserve dedicated

jerry cans for each water source. They should not be accessible to animals and should be frequently cleaned and disinfected.

If jerry cans are used to transport water from polluted sources for household water treatment, filled jerry cans should be stored in the dark to reduce algae growth. Biofilms and precipitate due to the settling of bacteria and particles can still form in the dark, however, so jerry cans that transport contaminated water still need to be regularly cleaned and disinfected to reduce the load on household water treatment systems.

Water transported by one person (with the typical size jerry can) is likely to be sufficient to cover daily drinking, cooking, food hygiene, hand-washing and face-washing needs. However, adequate quantities for bathing and laundry are likely not sufficient, nor for hand-washing where enhanced hygiene behaviour is required, such as during infectious disease outbreaks (WHO, 2020).

⊕ **Advantages**

- Available almost everywhere and robust
- Very low-cost
- Easy to clean
- Broadly accepted way of carrying water when distribution systems are lacking
- Available in different volumes

⊖ **Disadvantages**

- High risk of water recontamination when not cleaned regularly and properly, when there is no lid, or when the general condition of the jerry can is poor
 - Time spent carrying water is lost for other activities, such as work and school
 - Heavy for children to carry
 - May not provide sufficient water quantity for all hygiene needs.
-

→ References and further reading materials can be found on page 217.

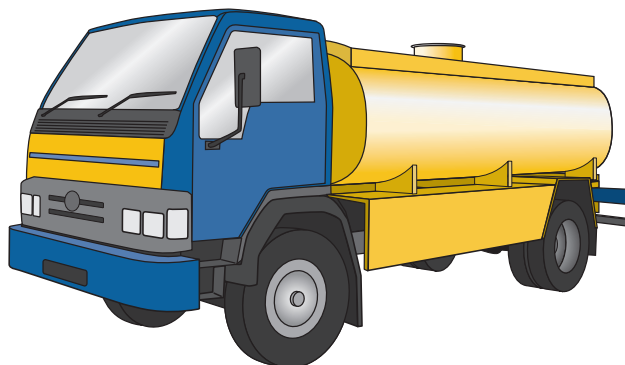
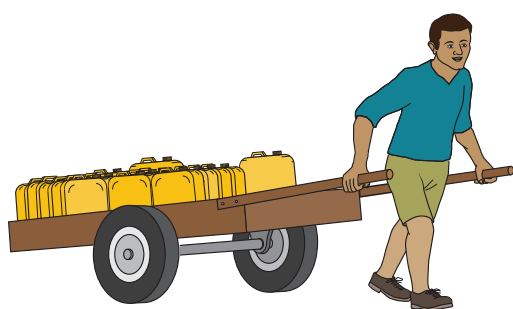
D.2 Water vendors (carts and trucks)

Applicable to systems
3, 4, 5, 6, 7

Management level
Household, community,
neighborhood, decentralized

**Local availability of technology
or components**
Yes

Technology maturity level
Established technology



Water vendors are individuals who obtain water from the source, private or municipal taps, wells, water kiosks, or public water-vending points and sell it to users directly.

Water vendors range from individuals who carry water in containers, push charts, or bicycles or deliver it in jerry cans with carts driven by animals or vehicles (e.g. motorcycles, tuk tuks, tanker trucks). Reselling this water can be either formal (water trucks managed by utilities or communities) or informal, such as individuals who buy or fetch water at the source and carry it to individual homes or other convenient locations for reselling at a higher price.

Applicability and adequacy

Water vendors are usually found in areas disconnected from the public water supply network, where distances to open water sources or community taps are large or the queue time is high.

Water vendors often operate as an extension of the public supply in urban areas, and they fill the gap between supply and demand. In rural areas, a long distance to water sources is often the driving force for water vendors. In areas where free or low-cost water sources are available, people who have income-generating activities might not have time or desire to fetch water on their own, meaning they may also rely on water-vendor services. Water vending should be considered an interim solution before the installation of adequate distribution systems.

Operation and maintenance

Carrying water is a physically demanding activity. Additionally, distributing vendors may collect water from the same sources as people would normally use for their households, meaning they cannot easily charge a high price for their labor. Competition is also often quite high, which keeps the prices close to those at the water source, and the subsequent earnings of water vendors are low. Road conditions, distance, and elevation all affect the effort that is needed to collect and deliver water. Vendors often rely on their own or rented vehicles, which require regular maintenance. Vehicle damage occurs often due to frequent overloading and lack of maintenance.

The water vending containers or tanks (and associated hoses and fittings) should be cleaned and disinfected regularly, and maintained in a sanitary and working condition at all times.

Health and environmental aspects/Acceptance

Since most of the services provided by individuals are informal, limited to no quality control is typically performed. Therefore, the quality of water supplied by water vendors is generally considered as low. This may or may not be true, depending on the water source, sanitary state, and condition of water-transporting vessels (jerry cans or tankers), free chlorine residual concentration in the supplying water, storage time, and water handling practices. Water transported formally by tankers is often collected in official water vending points, usually from the network, and is often of better quality.

Water can become easily recontaminated during transport. Old leaking containers should not be used for storing treated water. Containers should be dedicated to transporting drinking-water and not used for other purposes. Recontamination can be reduced when jerry cans or other containers are tightly and properly sealed after filling. Water ageing and stagnation in containers and tankers can cause taste and odour problems, free chlorine residual depletion, recontamination, and microbial regrowth.

⊕ **Advantages**

- Water is delivered to the door, which saves time for other activities
- Households can purchase small quantities at flexible prices
- Water vending can extend the service range of public utilities and provide an alternative solution when public utilities fail

⊖ **Disadvantages**

- Higher costs compared to water obtained through household connections and water sold at standpipes, boreholes, or water kiosks.
 - No quality control and often poor quality water is supplied
-

→ References and further reading materials can be found on page 217.

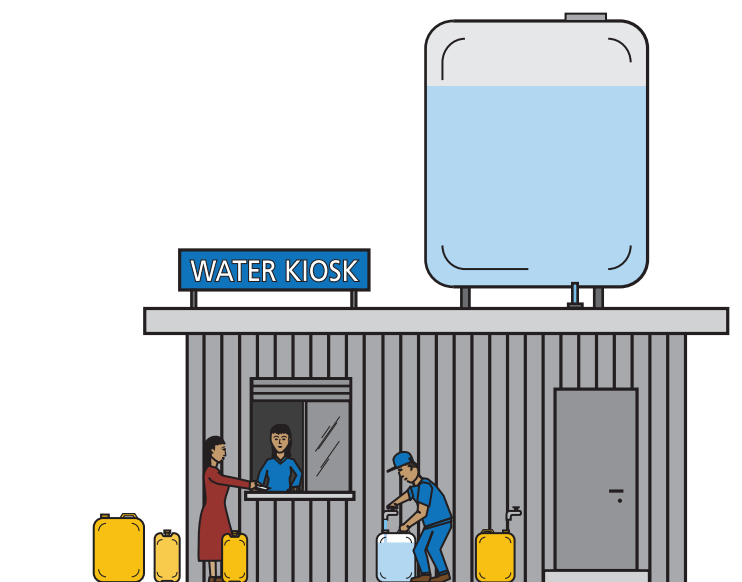
D.3 Water kiosk

Applicable to systems
3, 4, 5, 6

Management level
Community, neighborhood,
school/health center,
decentralized

**Local availability of technology
or components**
Yes/sometimes

Technology maturity level
Not long in use



Water kiosks are small shops that sell ground-water, tap water, or surface water. Water can be stored at these kiosks, or treated and stored (e.g. by a small decentralized on-site treatment system). Water kiosks can be operated by utility employees, self-employed operators, contractors, or water committees consisting of employed staff or volunteers.

Water kiosks are usually structures or buildings that have multiple taps outside and major taps inside the kiosk. They can be operated with or without a kiosk attendant, instead using an automatic mobile phone payment or card payment system (water ATMs). Water storage tanks close to the kiosks cover water sales in case of intermittent supply or water shortage periods. Water treatment systems are installed when raw water quality is poor or not reliable. Usually, a population of 200–3000 people can be served with one water kiosk. The capacity of a kiosk depends on the availability of raw water, water storage capacity, treatment capacity, and demand.

Applicability and adequacy

Water kiosks selling tap water to consumers can be installed in densely populated low-income settlements where access to tap water is not available (such as in informal settlements). Water kiosks are also used when the tap water supply is intermittent, and the

kiosk has the water storage capacity to cover interruptions. In densely populated urban middle- or high-income areas, these kiosks can sell water that has been post-treated to a high quality, often filled in bottles or clean jerry cans. Water delivery services may be offered by kiosks as well. In peri-urban areas lacking distribution networks, water kiosks sometimes replace public standpipes to more easily collect fees and reduce the risk of damage to the standpipes and community water points. In rural areas, kiosks are typically less common, though may be used when other water sources are not available or when awareness of the risks associated with unprotected water sources is high, providing a demand for treated water from a kiosk. The sale price can either be a flat rate per month, which can be collected at once or in small payments, or a price per jerry can or bottle. Making a water kiosk commercially viable is one of the largest problems to be addressed, which can be done by careful business planning, proper management, and sometimes by selling other household commodities or services alongside the water.

Operation and maintenance

The operation of water kiosks depends on the technology involved. If water kiosks sell only treated water from the main distribution network, the operation involves maintaining a clean area, collecting and recording charges, and operating the main tap. For water kiosks that involve storage, treatment, or water

bottling and distribution services, a higher level of maintenance and operation skills are required for equipment functionality, performing maintenance procedures (such as pump maintenance or filter cleaning), and keeping the cleanliness to a high standard.

Health and environmental aspects/Acceptance

The acceptance of water kiosks is low when other water sources are available and when the population is unaware of the health risks related to water quality. When water storage and treatment is done at the kiosk, proper management, operation, infrastructure maintenance, and quality control are essential. Without these points, the deterioration of the water quality or a failure in the treatment equipment will increase the health risks. To be successful, water kiosks need to deliver good services that satisfy the customers and reach their expectations regarding price, management, and operation. Enforcing regulations for water quality monitoring at a kiosk is quite difficult, especially for decentralized privately or community-run kiosks that do not belong to water utilities. Often, water costs more at a water kiosk than at privately-owned household connections. However, in unsupplied areas or for a population that cannot afford to pay the installment costs for a connection, a water kiosk is often the next cheapest option for safe water compared to mobile water vendors or bottled water. Water kiosks can also be used as a focal point for community engagement and awareness, with the trained kiosk operator providing best-practice advice on safe transportation/handling practices (including the use of safe collection vessels or the post-chlorination of jerry cans).

⊕ Advantages

- Water quality improvement if treatment is performed
- Treatment facility and water abstraction point are usually well managed
- Lower costs than bottled water or water vendors, flexible payment system
- Can be installed and implemented quickly, innovative technologies or concepts can be adapted to local conditions

⊖ Disadvantages

- Water quality deterioration after jerry cans are filled or during storage
- No or limited quality or service guarantees
- Choice of operator may influence kiosk success
- Higher costs compared to household connection

→ References and further reading materials can be found on page 217.

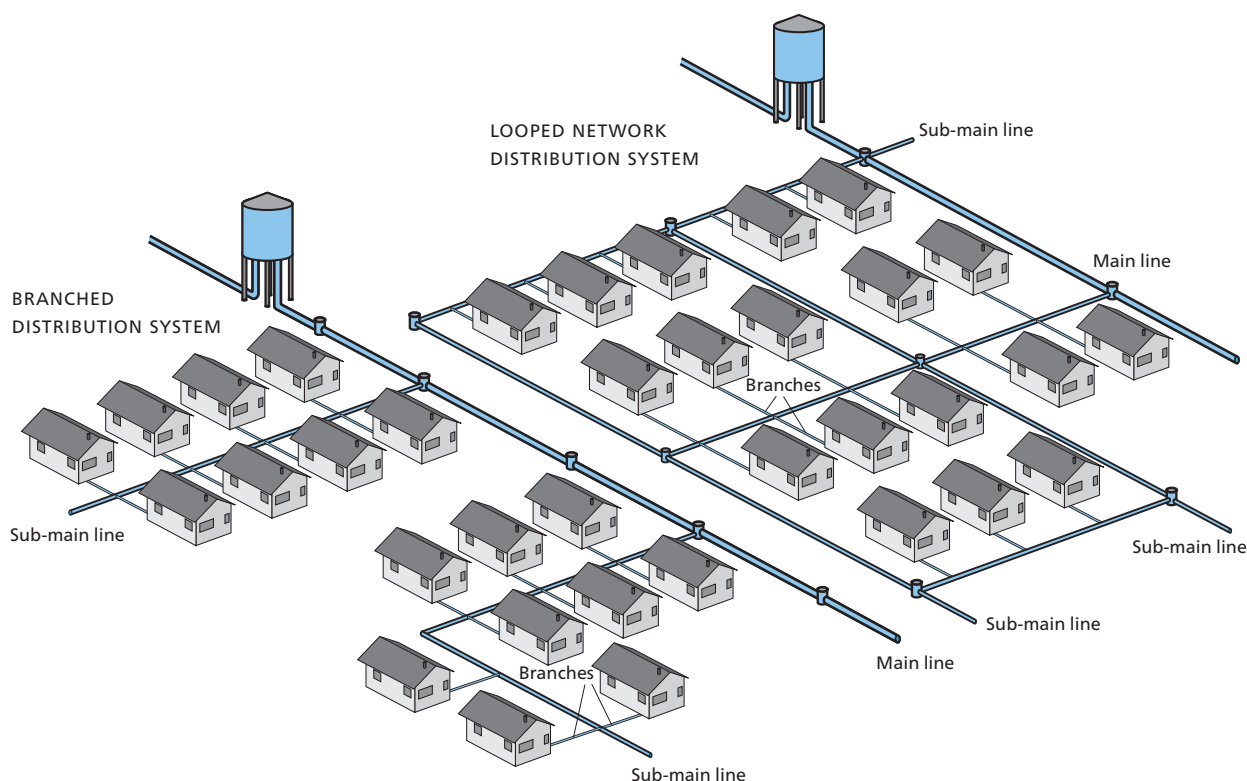
D.4 Small public and community distribution system

Applicable to systems
3, 5, 6, 7, 8

Management level
Community, neighborhood,
decentralized

**Local availability of technology
or components**
Yes

Technology maturity level
Established technology



Water distribution systems transport water from the water source or water treatment plant to the point where it is delivered or used, such as a community standpipe, yard connection, or household connection.

Water demand in small public and community distribution systems varies during the day. The highest consumption is during the hours common for personal hygiene, washing, and cooking, and the lowest consumption is at night. These variations need to be addressed by water storage or pump control mechanisms. In small public and small community water supplies, a storage reservoir is the preferred option. It should also be the preferred option when electric power or diesel supply is unreliable. Storage reservoirs accumulate water at night or when energy is available and supply it during peak water demand hours. A pressure of at least 5–10m of the water column is needed to prevent the ingress of polluted seepage water, to protect the integrity of the water supply network, and to ensure sufficient pressure in the taps.

There are two types of small public and community distribution networks. The branched network consists of one or a few mains that separate into several dead-end connections. Looped or grid configurations consist

of one or a few main loops (rings) from which water is conveyed to secondary loops or branches. Branched networks are simple to design and easier to install than looped networks. They are often used in small community distribution systems. Looped networks require many interconnecting pipes, valves, and special parts, and are more complex and expensive than branched ones, though these networks improve the hydraulics of the system and are generally more reliable. Pressure variations are usually reduced with looped networks. Additionally, water can be supplied from different directions, which can be important when one of the loops needs to be maintained. Water stagnation is less likely, reducing the risk of sediment accumulation and microbial recontamination.

In these distribution systems, water is delivered to the house, yard, or community standpipe. A household connection taps into the distribution main by a T-part or a special insert piece and delivers water inside the house to one or multiple taps. A yard connection is similar, though is placed outside and may supply more than one household. Public standpipes have one or more taps and occasionally a platform for containers of different sizes. Public standpipes should be located within 500m or a 30 minute walking time from the households they supply.

Applicability and adequacy

Community and small public water distribution networks are designed to supply water for personal and household needs as well as occasionally for animals and the irrigation of gardens. They are more common in urban and peri-urban areas. In rural areas, larger villages and their surrounding houses may have a simple network with household or yard connections or public standpipes. Because the construction is complex and requires substantial investment, proper design and planning are essential. Water consumption also increases greatly when it enters the house; water consumption at standpipes usually varies between 20–30 L per person per day, while directly connected households may consume 100 L or more per person per day depending on the type of washing facilities and equipment and the availability of a flush toilet. Although household connections are often the most desirable option for users, a public standpipe might be the simplest and most cost-effective way to provide water to a large number of users. Often communities do not even allow a household connection to be installed, and the cost to adequately dispose of the wastewater generated through household connections also needs to be considered in the overall cost assessment. It is possible to develop the distribution network in stages, but this should be addressed carefully during the planning stage.

Operation and maintenance

Leakage is usually the most important problem and also the reason for unaccounted and/or non-revenue water. Various reasons for leakage include soil movement (e.g. drought, erosion, traffic loading), defects and poor construction work, inferior pipes and joints, damage due to excavation for other reasons, ageing, corrosion, high pressure or temperature changes, illegal connections, and mains tapping. Leakage can be managed through regular checks by water committees, caretakers, or small public water supply utilities as well as alert systems and an estimation of the water balance by water flow or pressure measurements. Leak detection equipment, such as an acoustic detector or leak noise correlator, can be used to detect leaks not visible on the surface.

Poor design of the pipes and structures may cause severe corrosion even when appropriate materials are used. In addition to optimized network design and material selection, corrosion should be managed by optimizing the water chemistry (e.g. hardness removal, pH optimization). Corrosion deposits and sediments due to improper treatment or recontamination need to be removed by flushing, swabbing (or pigging), or air scouring. Pipe disinfection can be done using chlorine at high doses, and the proper disposal of flushed water should be considered.

Health and environmental aspects/Acceptance

Small public and community piped water systems provide good quality water when managed properly. Water wastage from standpipes and non-metered household/yard connections caused by broken taps or misuse is a serious problem. Water wastage can be reduced through the improvement of management structures, which can be financially supported through fees at standpipes or water metering. Problems with spilled water drainage can lead to the formation of small ponds of stagnant water, which present a serious health risk. Intermittent water supply may cause water stagnation in the network pipes. This usually leads to the depletion of free chlorine residual concentration. A pressure reduction or negative pressure during intermittent operation increases the risk of groundwater infiltration and ingress or contamination via wastewater in the distribution network. An intermittent water supply leads to people storing water in households in unsafe storage containers. With public community standpipes, water is transported to households by jerry cans or buckets (D.1 Jerry cans), and recontamination is a common problem here, as well.

⊕ Advantages

- Distribution network with household connection is the most convenient and desired way of distributing water for users
- Lower level of contamination compared to water carried in jerry cans and trucks
- During continuous supply, no need for safe water storage or household water treatment

⊖ Disadvantages

- Consumption and wastage increase when household connections are used, proper disposal of grey or black water is needed
 - Contamination during intermittent operation
 - Supply breakdowns and interruptions due to maintenance works or the deterioration of poorly managed infrastructure
-

→ References and further reading materials can be found on pages 218.

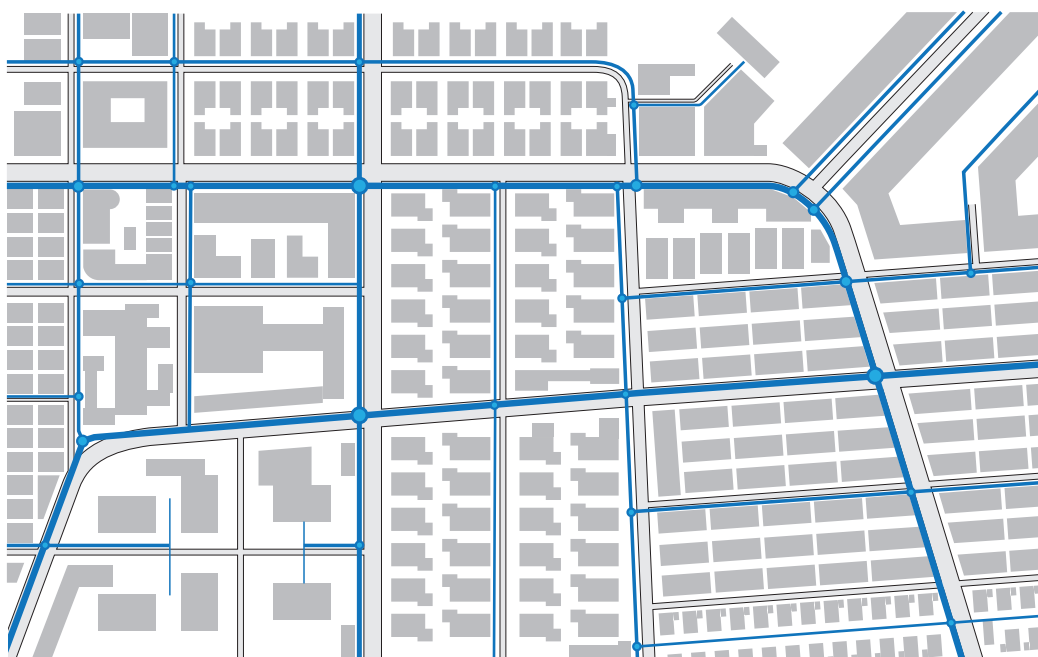
D.5 Centralized distribution systems

Applicable to systems
2, 8, 9

Management level
Centralized

Local availability of technology
or components
Yes

Technology maturity level
Established technology



Centralized water distribution systems transport water from the water source or water treatment plant to the point where it is delivered or used, usually consisting of household connections with multiple taps through a complex interconnected underground network of pipes.

Centralized distribution networks must be designed and constructed in a way that dead-ends are eliminated, flushing is possible, and cross-connection and unauthorized access are prevented. The design must allow adequate disinfection and ensure that the capacity of the water system is sufficient to meet the domestic demands of the users connected to the network. Most centralized urban distribution networks have a looped configuration, which is more reliable than branched configurations. The design considerations involve the topographic features of the terrain, economic parameters, and fluid properties. The essential parameters of the network size are the projection of residential, commercial, and industrial water demand, pipe material, and reliability considerations. The design period, which is the time period the system is designed to function for, is limited by the lifespan of the pipes and equipment.

Applicability and adequacy

Centralized distribution networks are designed to supply water for domestic needs as well as the water needs of organizations, enterprises, firewater reservoirs, emergency water supply reservoirs, etc. In many countries, the required capacity for firefighting will have a major impact on the capacity of the entire water supply system. Centralized distribution systems are common in urban and peri-urban areas. In rural areas, a centralized water distribution network is prohibitively expensive, and community-scale water supplies are often used. The planning, design, and construction of centralized distribution systems are complex, require a high level of expertise, especially when multisource systems are needed, and require huge investments. Nearly 80–85% of the costs of the water supply of a city are required for the distribution network. Average water consumption at households connected to a centralized water system with multiple taps and a flush toilet varies between 100–400L per person per day, including losses due to leakage. This consumption level is considerably higher than for households collecting water at public taps, wells, or other decentralized sources without a household connection, as well as households with one tap on premises (WHO, 2020). The distribution network can be

developed in stages, but such expansions should be addressed carefully upfront during the planning stage.

Operation and maintenance

Leakage is usually the most important problem and also the reason for unaccounted and/or non-revenue water. Various reasons for leakage include soil movement (e.g. drought, erosion, traffic loading), defects and poor construction work, inferior pipes and joints, damage due to excavation for other reasons, ageing, corrosion, high pressure or temperature changes, illegal connections, and mains tapping. Leakage can be managed by regular checks by water utility staff or water committees, alert systems, and an estimation of the water balance by water flow or pressure measurements. Leak detection equipment, such as an acoustic detector or leak noise correlator, can be used to detect leaks not visible on the surface. Efficient cross-connection management practices are crucial. Poor design of the pipes and structures may cause severe corrosion, even when appropriate materials are used. In addition to optimized network design and material selection, corrosion should be managed by optimizing the water chemistry (e.g. hardness removal, pH optimization). Corrosion deposits and sediments due to improper treatment or recontamination need to be removed by flushing, swabbing, or air scouring. Pipe disinfection can be done using high doses of chlorine, and the proper disposal of flushed water should be considered.

Health and environmental aspects/Acceptance

Centralized distribution systems provide good quality water when managed properly. Water wastage from non-metered household connections caused by broken taps or misuse is a serious problem. Better management structures are often needed to reduce water wastage.

An intermittent water supply may cause water stagnation in the network pipes and/or the depletion of the free chlorine residual concentration. Reducing the pressure or a negative pressure during interruptions can lead to groundwater or wastewater infiltration and ingress in the distribution network, often resulting in contamination. An intermittent water supply leads to people storing water in households in non-safe storage containers, which also leads to contamination.

- During continuous supply, no need for safe water storage or household water treatment
- Water can be used for multiple purposes

⊖ Disadvantages

- Consumption and water wastage are considerably higher than with other types of water transport and distribution; proper sanitation systems are needed
- Contamination during intermittent operation due to inadequate free chlorine residual concentrations
- Supply breakdowns and interruptions due to maintenance works or the deterioration of poorly managed infrastructure
- High investment and management costs
- Needs proactive maintenance and long-term planning to manage ageing infrastructure

→ References and further reading materials can be found on page 218.

⊕ Advantages

- Distribution network with household connection is the most convenient and desired way of distributing water for users
- Usually good quality and lower level of contamination compared to water carried in jerry cans and tracks

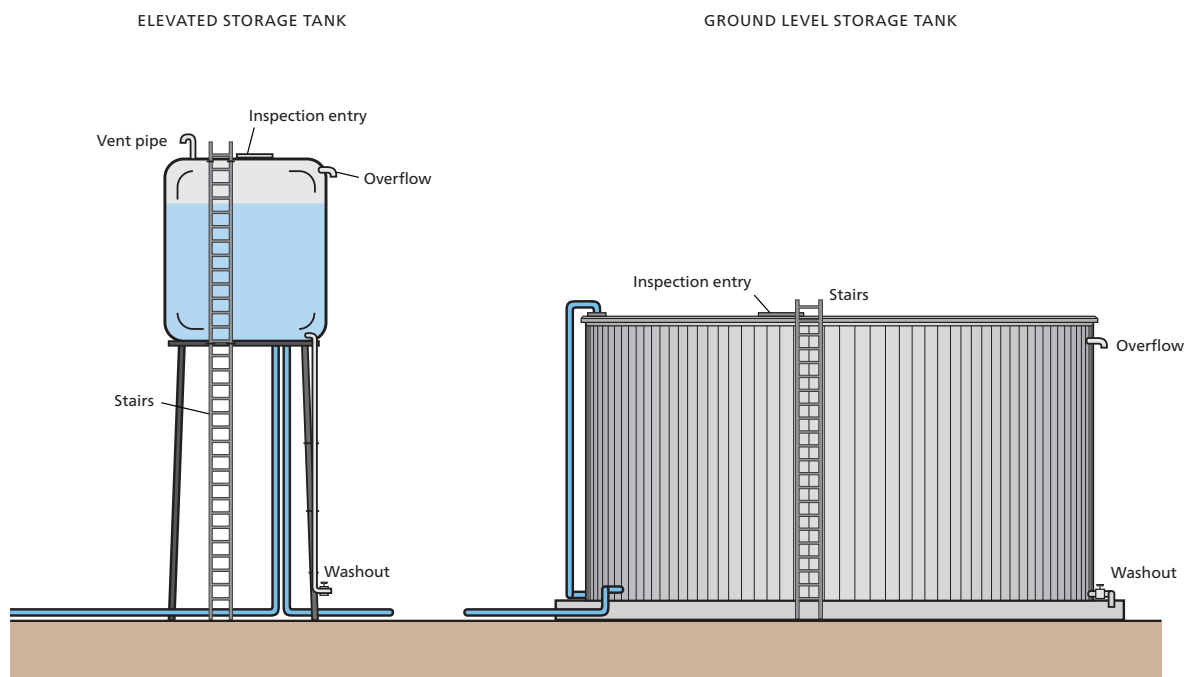
D.6 Storage tanks or reservoirs

Applicable to systems
1, 2, 3, 5, 6, 7, 8, 9

Management level
Community, neighborhood,
school/health center,
decentralized, centralized

**Local availability of technology
or components**
Yes

Technology maturity level
Established technology



Water storage tanks or reservoirs are an integrated part of water supply and distribution systems. They are used to store raw water after abstraction or treated water close to the point of use. Elevated water tanks – also called water towers – are used as a reserve to overcome power supply shortages or during peak usage times as well as to provide stable hydrostatic pressure in the network.

The storage tanks or reservoirs can be classified by their capacity, purpose/type of stored water, elevation, design, type of material, and construction method. For storing raw water, concrete-lined earthen reservoirs can be used. They can be built in natural depressions and have sloped inner and outer walls. When concrete is used, it can be either poured on-site in large slabs, which are then sealed, or a single-lining slab can be constructed on-site using ferrocement technology. The infiltration of water is prevented by lining the concrete using high density polyethylene (HDPE) plastic, butyl rubber, or clay.

Good quality water (safe groundwater or treated water), can be stored at ground level, underground or in elevated reservoirs. Concrete reservoirs reinforced with steel mesh or bars are typically used, which require

a solid foundation to stabilize the reservoir. Those reservoirs should be covered to prevent contamination and cyanobacteria/algae growth, as well as to prevent unauthorized access. A water inflow pipe is placed above the water level to reduce the risk of back-flow. An aeration pipe should be protected by a screen to reduce the risk of recontamination and access by animals. Water can be chlorinated at the inlet of the tank to provide residual protection. Tanks made of ferrocement are produced by covering the steel mesh or wire with a thin layer of cement and sand mortar and are lighter and more flexible. They are round to increase their stability.

Elevated reservoirs are usually constructed at the height required to pressurize a water distribution system. An elevated support structure that is massive enough to carry the weight of the tank and water is used. The water towers can be built out of reinforced concrete, steel, or a combination of materials (e.g. of steel structures and plastic tanks). The towers can be cylindrical, rectangular, or any other shape convenient for construction. When made of steel, the typical construction consists of factory-made galvanized steel elements welded together. A robust and reliable foundation is crucial. The flow level of the tank is usually regulated by a flow switch or a sensor connected to

the pump that fills the reservoir. In addition to the inlet and outlet pipes, the tanks require washout and overflow pipes. In community and large-scale systems, the water towers are often constructed in conjunction with underground or surface reservoir systems. Tank filling can occur on-demand or only at specified times, e.g. during the day when solar-powered pumps are used for refilling or during the night to profit from reduced power prices. The systems are sized to cover the peak needs and at least a one-day demand. Water towers can also be designed to cover the needs of fire protection services (required by regulations in some countries), and in this case, the capacity will considerably exceed the drinking-water demand.

Applicability and adequacy

Water storage tanks can be made out of various materials and in various capacities, from a few cubic metres to many thousands. For community supplies, earthen or surface concrete tanks are usually not more than 1.5–3 m deep. The lifespan of most concrete and ferrocement tanks is at least 30 years when maintained properly. Due to corrosion, galvanized steel tanks can have a shorter life expectancy. Plastic PVC tanks exposed to sunlight might need to be replaced after only 10–15 years.

Operation and maintenance

The operation of most reservoirs and tanks includes opening and closing the valves according to the water needs. The valves should also be closed and opened at least once every two months to avoid sticking and blocking. Storage tanks and reservoirs need to be routinely drained, cleaned (including sediment removal) and disinfected. The lining also must be regularly inspected for cracks and leaks. A surface or elevated reservoir storing safe drinking-water needs to be controlled regularly for possible sources of contamination. This includes checking whether screens and manholes are closed and intact and the surrounding area is protected from access by animals or children, as well as for the appearance of cracks and leaks. When galvanized steel is used, the tanks should regularly be controlled for signs of corrosion. The elevated steel tanks would require protection from lightning. The water level in the towers typically falls during peak use time, and the tank is filled again by the pump during low consumption times. In cold climates, this process is crucial for protecting the water from freezing. The foundations of the concrete tanks, when poorly constructed, can be damaged due to soil settling. Continuous chlorination should be practiced whenever possible for tanks storing treated water. Where this is not possible, regular batch disinfection of the tanks is the minimum requirement. The area around water tanks should also be well-drained and unlikely to flood.

Health and environmental aspects/Acceptance

The risk that a collapsing water tank can cause to the local population should be always considered. Poorly closed or open water tanks can serve as a breeding ground and watering place for mosquitos and other vectors. Additionally, rodents, birds, and other animals can easily become trapped inside the tanks. Poorly designed inlet/outlet structures can result in short-circuiting flow,¹⁴ which can lead to low-flow zones and issues associated with excessive water age and stagnation (taste/odour, chlorine decay, and microbial regrowth/recontamination) and inadequate contact time (e.g. where disinfection is practised). Where underground storage tanks are in use, appropriate design, maintenance and drainage is required to prevent surface water contamination.

+ Advantages

- Different designs for the entire range of capacities and needs are available
- Water storage tanks compensate for peak demands and power supply breakdowns
- Elevated water tanks provide stable hydrostatic pressure in the distribution network

– Disadvantages

- Risk of contamination during inadequate storage
 - Risk of leakage and water loss
 - Open or poorly covered tanks can serve as vector breeding grounds
 - Usually high cost
-

→ References and further reading materials can be found on page 218.

¹⁴ When the flow of water follows a more direct route from the inlet of a storage tank/basin to the outlet, which may result in poor mixing and shorter actual detention/contact times than was designed for.

This section describes household water treatment and safe storage technologies that can be used as single-stage water treatment alternatives when centralized or community-scale treatment are not available or the quality of the water supply is inadequate. When water contamination occurs during transport between the public tap or water source and home, household water treatment can improve the situation. Drinking-water should be stored safely in all cases.

The following methods and technologies are summarized in this chapter:

H.1 Storage tanks or reservoirs

H.2 Ceramic filtration

H.3 Ultrafiltration

H.4 Chemical disinfection

H.5 Boiling

H.6 Pasteurization

H.7 Biosand filtration

H.8 Ultraviolet (UV) light disinfection

H.9 Solar water disinfection

H.10 Fluoride removal filters

H.11 Arsenic removal filters

The choice of household water treatment method and its successful implementation depends on several factors, including:

- Quality of water and type of contamination
- Level of protection required
- Local availability of, or access to, products, consumables, or spares
- Price of hardware and consumables
- Quality of manufacturing
- Willingness to pay for hardware and consumables
- Cultural preferences for a certain treatment method
- Motivation and awareness of consumers regarding water quality problems
- Quantity of water to be treated
- Available space
- Available energy sources

There is a wide variety of household water treatment products available on the market that vary in performance with respect to contaminant removal. In light of this challenge, the World Health Organization (WHO) established a scheme to independently evaluate the contaminant removal performance of the growing number of available household water treatment products. The scheme, one part of WHO's normative programme on drinking-water quality, informs the procuring agencies of member states and the United Nations (UN) of effective household water treatment technologies to reduce the risk of diarrheal disease from unsafe drinking-water. The performance of the products is classified according to the three levels of protection, as summarized in the table below.

In particular, the scheme helps to ensure that products providing limited to no pathogen removal are kept off the market. The results of the evaluation rounds show that the performance of the same technology in different products varies strongly, and a few products have failed to meet the minimum performance criteria. It is likely that their performance under actual use conditions, especially where use instructions are not followed or are unclear, is worse. It is therefore essential that procurers make an informed selection based on a detailed consideration of candidate product performance data and that there is improved government regulation of household water treatment to keep poor performing products off the market. For more information on WHO's International Scheme to Evaluate Household Water Treatment Technologies, including the list of products tested and their performance, visit <https://www.who.int/tools/international-scheme-to-evaluate-household-water-treatment-technologies>.

This chapter summarizes the major principles and characteristics of the different technologies without focusing on specific products. The performance of the technology, however, ultimately depends on user operation and quality control during production and assembly. The design, implementation strategy, education, promotion, and marketing strategies are critical for user acceptance.

See Annex 2 for a summary of technological interventions at the user level.

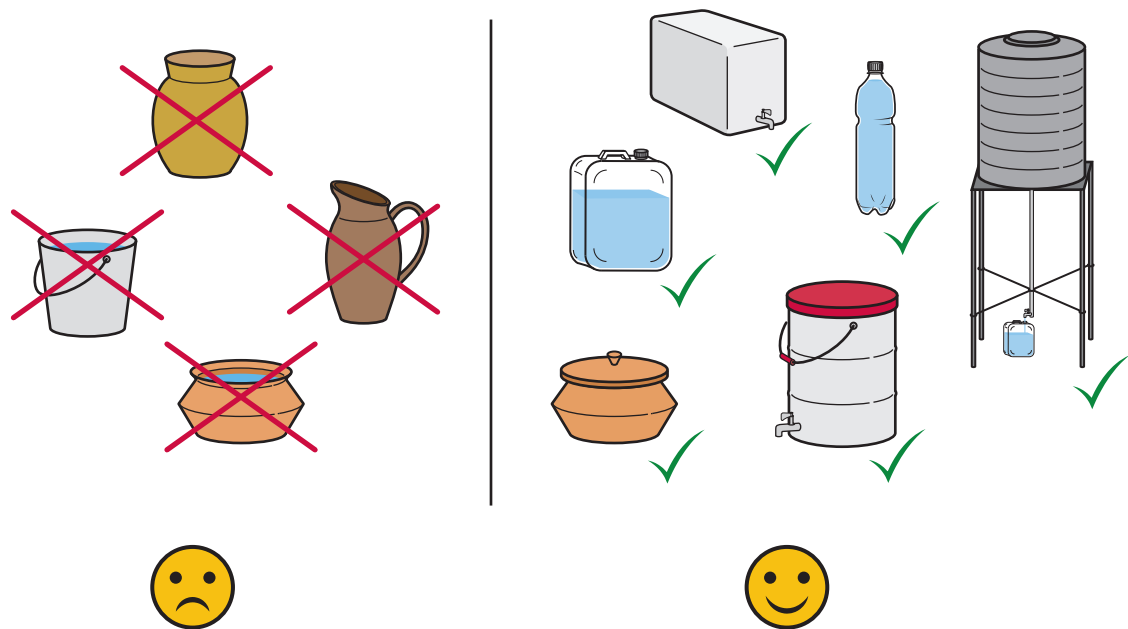
Table 2

WHO performance criteria for HWT technologies (after WHO, 2019a)

Performance classification	Bacteria (log ₁₀ reduction required)	Viruses (log ₁₀ reduction required)	Protozoa (log ₁₀ reduction required)	Interpretation (with correct and consistent use)
★★★	≥ 4	≥ 5	≥ 4	Comprehensive protection
★★	≥ 2	≥ 3	≥ 2	
★	Meets at least two-star (★★) criteria for two classes of pathogens			Targeted protection
—	Fails to meet criteria for one-star (★)			Little or no protection

H.1 Storage tanks or reservoirs

Applicable to systems 1, 2, 3, 4, 5, 6, 7, 8, 9	Management level Household, school, health center, neighborhood	Local availability of technology or components Yes/sometimes	Technology maturity level Established technology
--	--	---	---



Safe water storage uses containers that protect water from recontamination. The containers can be of various sizes (from 5 L bottles or pots to 1000 L water storage tanks to 5000 L containers on top of buildings) and are characterized by two main features: 1) the presence of a good cover and narrow opening for filling, and 2) the availability of a tap/spigot or connection to the in-house distribution network.

Containers can be placed inside the house or set up outside, such as underground in the yard, on the roof of the house, or on a specially designed tower. Small containers are usually filled manually. Larger water storage tanks are filled through a distribution network, rainwater harvesting system, or water tanker, and they are connected to the distribution network/tap in the house. The design of such safe water storage vessels should protect water from contamination during transport and in households and to reduce the risk of introducing pathogenic microorganisms and vectors, especially through contact with hands, cups, or implements for dipping (e.g. ladles, cups, buckets).

Applicability and adequacy

Safe water storage containers and tanks should be used in all cases where water is stored at households,

regardless of whether the water comes from a distribution network, groundwater well, or has been treated by a household water treatment device. Small containers used to store water carried from the source/tap outside of the house can be placed at the point of use. It is recommended that the same container be used for fetching water at the source and storing it to avoid contamination during the transfer of water from one vessel to another.

In houses with household or yard connections, storage tanks can be used to cover for intermittent supply. When sufficient tap pressure is available, tanks are placed on the roof of the house from where water is distributed by gravity to the taps within the household. In multistory buildings, the pressure in the distribution network might be insufficient for the upper floors, which will require a pressure boosting system. In systems with an intermittent water supply, water can be pumped from a ground level or basement tank to a gravity roof tank. The size of the tank depends on the water demand and the availability of adequate pressure in the network.

When rooftop or yard tanks are used for different purposes (i.e. irrigation, watering of animals), there is a risk of contamination through different connections. Therefore, this should only be done with backflow prevention valves and cross-connection control devices.

Large tanks must be installed on bases or platforms that can bear the weight of the tank when it is filled to maximum capacity. No water storage container should be placed in proximity to or under any sanitary plumbing or systems with non-potable water to avoid cross-contamination. The storage containers should be easily accessible for inspection and maintenance. A metal tank and its support structure should be separated by a non-corrosive insulating material to prevent corrosion.

Operation and maintenance

Cleaning with soap and a chlorine disinfection after cleaning are crucial to prevent water recontamination with pathogenic microorganisms as well as the formation of biofilms or precipitates after filling the container. While abrasive materials can effectively clean water containers, they may also damage the internal surface, providing a greater surface area and niche for microbial growth that is more challenging to remove during subsequent rounds of cleaning. Low-quality plastics can become brittle when exposed to sun and heat over a long period. Therefore, water storage containers should not be placed in direct sunlight for extended periods when possible. Exposure to sunlight can also cause algal growth in transparent and opaque containers. Low-quality taps leak relatively often and need to be replaced to avoid water wastage.

Large tanks placed on roofs or in yards also need to be drained or flushed and disinfected routinely. They can serve as breeding places for mosquitos or other vectors and can trap rodents and birds if not properly closed and sealed to the external environment. Thus, the lids need to be checked regularly. When valves are used, they should be closed and opened at least once every two months to avoid sticking and blocking. All tanks should be routinely inspected for cracks, deformation, sediment accumulation, and leakages. The safe storage containers should be protected from animal access.

Health and environmental aspects/Acceptance

The safe transport and storage of water at home is essential for preventing water quality deterioration after it leaves the source and before consumption. Safe water containers are well accepted and convenient to use, though the higher costs as compared to open buckets and jerry cans can be a barrier for adoption. Proper maintenance is essential for containers and tanks at all scales. Missing lids, leaking taps, and cracks compromise the safety and/or acceptability of stored water. Hygiene promotion may be required to sensitize the population towards the use and maintenance of safe water storage containers and tanks. For rooftop and yard tanks, the risk to local residents caused by a collapsing water tank should be always considered.

⊕ Advantages

- Reduces risk of recontamination
- Reduces vectors that rely on open water

⊖ Disadvantages

- Costs more than open buckets or jerry cans
- Has higher breakdown rate due to taps compared to containers without taps

→ References and further reading materials can be found on page 218.

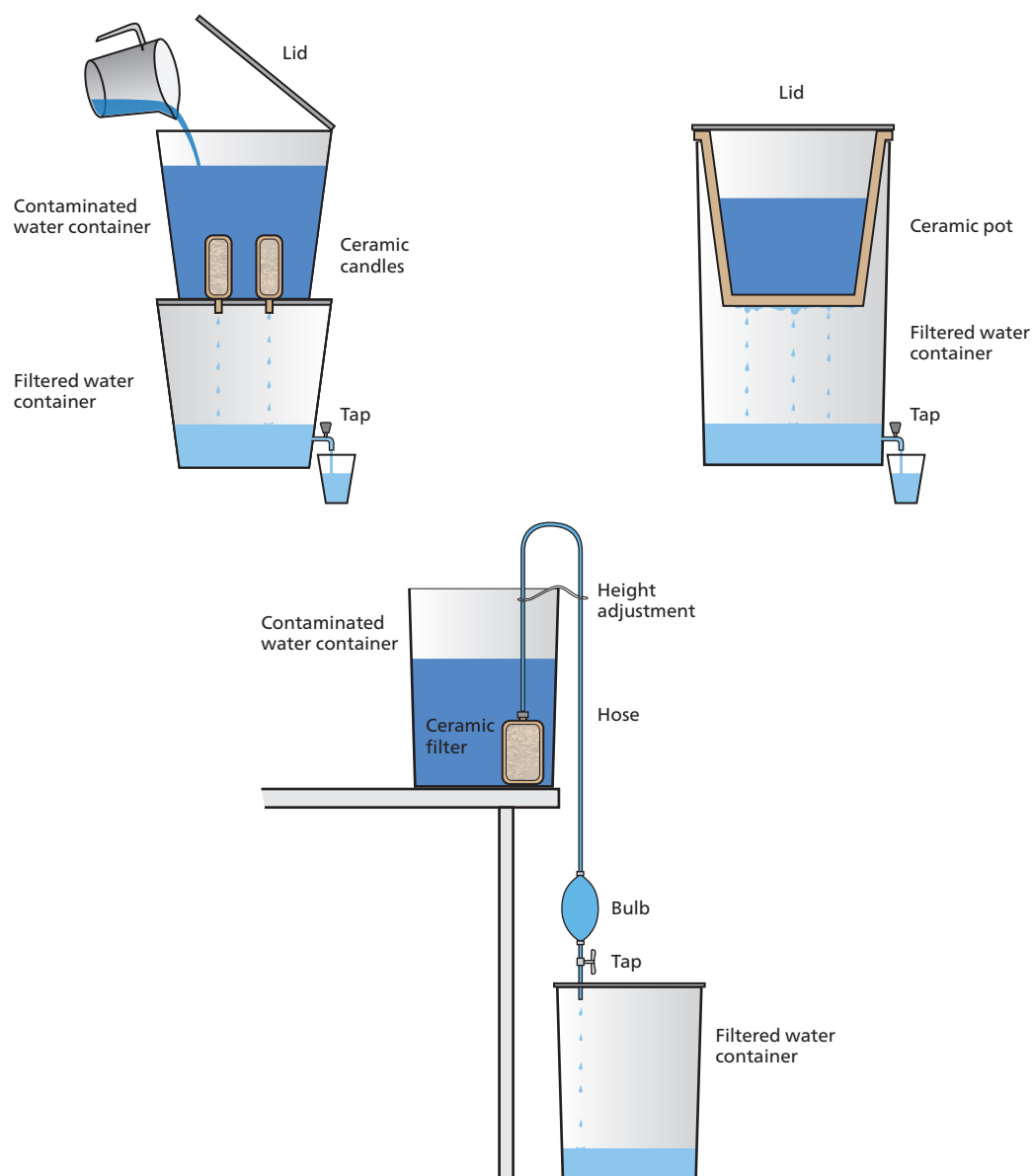
H.2 Ceramic filtration

Applicable to systems
1, 2, 3, 4, 5, 6, 7

Management level
Household

Local availability of technology
or components
Yes

Technology maturity level
Established technology



Ceramic filters are simple devices that use pots or candles made out of clay to filter drinking-water to remove turbidity and pathogenic micro-organisms.

Two containers made out of plastic, metal, or clay are stacked, and water is poured into the upper container, which is either a ceramic pot or a plastic/metal container containing ceramic candles. The water is gravity filtered through the pot or candle and is collected in the lower container, where it can be released with a tap. This device treats water and safely stores it until use. Ceramic pot filters can be constructed with locally

available material. Ceramic candles are usually imported and placed into the local containers.

Ceramic filters have pore sizes on the order of microns. The filtration of suspended particles and pathogenic microorganisms occurs through mechanical trapping and adsorption in the pores of the ceramic filter elements. Although silver is sometimes used in candles or pots to inactivate pathogens, or protect from recontamination, it is not considered an effective drinking-water disinfectant. Silver has generally been only found to be effective against bacteria (particularly *E. coli*) and only where there are long contact times. The limited studies on protozoa and viruses indicate

limited inactivation of protozoa and viruses, even after long contact times (WHO, 2018a; WHO, 2021c).

The efficacy of ceramic filters for removing pathogens varies depending on the type, production conditions, and quality of the ceramic element. In general, between 2–6 log reduction value (LRV) can be achieved for bacteria and protozoa, with lower removal efficiencies of between 1–4 LRV for viruses (noting that performance will vary depending on pore size, flow rate, and inclusion of augmentation with chemical agents [WHO, 2022a]).¹⁵ It is crucial to ensure that the ceramic filter elements are correctly fixed in the raw water storage tank to avoid leakage and recontamination.

Applicability and adequacy

Due to the limited flow rate (1–2 L/h) and storage capacity (about 10–15 L), the filters are suitable for use for small households. The filters are also suitable for water that is clear or has low turbidity (i.e. less than 5 NTU). For very turbid water (i.e. greater than 5 NTU), filter clogging may occur even with frequent cleaning. Pre-settling water with a high turbidity can help to extend the life of the ceramic filter elements. Ceramic filters can remove some iron and taste components to improve the smell and colour of the water. Some ceramic candles also contain activated carbon to further improve the taste and odour of water. The limited efficacy of virus removal should always be considered when using or promoting ceramic filters, since pathogenic viruses are an important cause of waterborne disease, including rotaviruses, a leading contributor to diarrheal diseases for infants and small children.

A robust supply chain and market availability for replacement ceramic candles and taps is required, as this may be a major limiting factors in the scale-up of this technology. Ceramic filters can be stacked for storage but still require a relatively large storage area. The fragility of the ceramic filter elements can lead to a high damage rate during transport.

The local manufacture of ceramic pots or even candles is possible. However, it requires good quality control and quality control standards. Clay composition varies with different geographical regions and can cause quality problems along with other production variables.

Operation and maintenance

Ceramic filters are very simple and daily operation is limited to filling the containers with water. Maintenance includes scrubbing the filters with a soft brush or cloth, which should be done frequently if turbid water is used. Chlorine or soap should not be used to clean the ceramic elements but can be used to clean lids, the clean water storage container, and the tap. The candles or pots should not be placed on dirty sur-

faces during cleaning and should not be fixed with dirty hands to avoid recontamination. Proper care should be taken when transporting ceramic filters, as the material is fragile and cracks that are barely visible can reduce the efficacy of the filters.

Health and environmental aspects/Acceptance

Ceramic pot or candle filters are well accepted. Removing turbidity makes water treatment visible, and the benefits are apparent and easy to understand for the users. Consumers often prefer filters to other household water treatment products, although they are less affordable and not the most efficient option compared to other technologies. The treated water storage container and tap may become recontaminated and should be regularly cleaned and possibly disinfected with chlorine.

⊕ Advantages

- Functions through simple, one-step filtration
- Requires no chemical additives
- Has high acceptance
- When maintained properly, filters are durable

⊖ Disadvantages

- Limited to no protection from viruses
- Removes bacteria and protozoa to a varying degree depending on the manufacturing quality
- Breaks easily if dropped; cracks are not always visible
- Clogs during filtration of turbid water
- Has relatively short lifespan (filter candles)
- Provides no residual disinfection (safe storage/handling must be practised post-treatment)
- Has limited affordability

→ References and further reading materials can be found on pages 218 and 219.

¹⁵ For product specific LRVs, refer to WHO's International Scheme to Evaluate Household Water Treatment Technologies: <https://www.who.int/tools/international-scheme-to-evaluate-household-water-treatment-technologies/products-evaluated>

H.3 Ultrafiltration

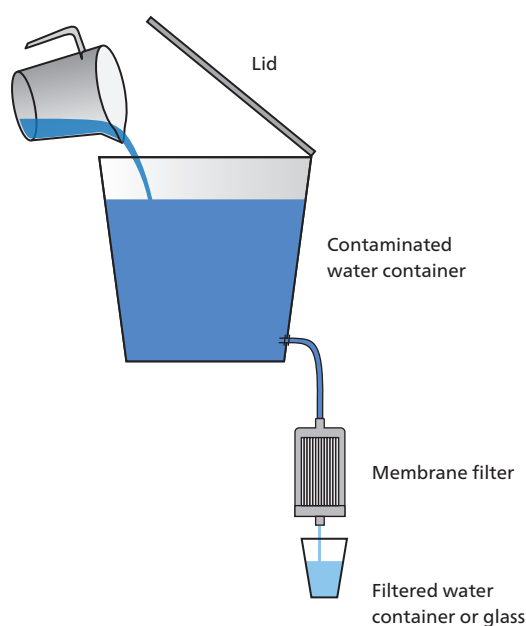
Applicable to systems
1, 2, 3, 4, 5, 6, 7

Management level
Household, school, health
center, neighborhood

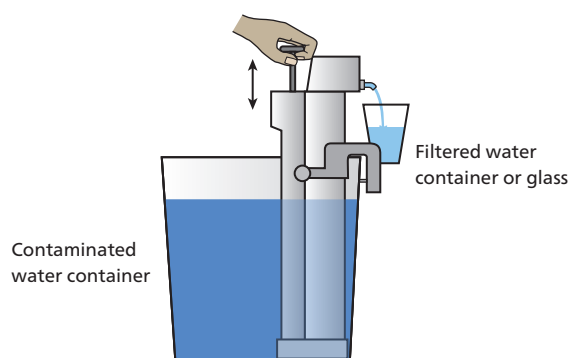
Local availability of technology
or components
Sometimes

Technology maturity level
Established technology

MEMBRANE FILTER BY GRAVITY



MEMBRANE FILTER BY PRESSURE
(HAND PUMP)



Ultrafiltration membranes are polymer filter sheets or hollow fibers that have pores of 0.01–0.08 μm . The membrane is packed in cartridges through which water is filtered by gravity or pressure generated by manual pumping. Most bacteria, viruses, protozoa, and larger organisms are retained on the membrane surface through a combination of processes such as size exclusion and adsorption. The pore size, membrane properties, and the manufacturing quality determine the performance of the filters.

Microorganisms and particles are retained on the membrane surface during filtration. This retained material forms a layer on the membrane over time, reducing the flow rate. Flow through the membrane system depends on the membrane characteristics (permeability), surface area of the membrane used in the filter, the applied pressure, and the degree of fouling caused by the raw water. Fouling is typically caused by a high level of natural organic matter and turbidity in raw water. For gravity driven systems, new membrane modules can provide over 40 L/h of treated water per 1 m^2 of the membrane with 100 cm of hydrostatic pressure difference. Microfiltration membrane

filters can sometimes be found on the market, and these filters have a higher flow rate but also larger pores (0.1–1 μm). They therefore may provide more limited virus removal if no other treatment is used.

Applicability and adequacy

The performance of the membrane filters in removing pathogenic microorganisms is defined by the pore size distribution of the membrane, the quality of the membrane material, as well as the manufacturing quality of the produced modules. Although ultrafiltration membranes perform reliably, the quality of products may vary considerably. When production quality is assured and verified, ultrafiltration filters are one of the most reliable technologies on the market for the removal of protozoa and bacteria, achieving 3–6 log reduction value (LRV) (noting that performance may vary depending on the integrity of the filter medium and filter seals, and resistance to chemical and biological ("grow-through") degradation [WHO, 2022a]). For virus removal, the performance of the membranes depends on the pore size and the distribution of the pores. In general, membranes with a small pore size (20 nm or less), narrow pore-size distribution, and high manufacturing quality show very good virus removal

(up to 6 LRV; WHO, 2022a).¹⁶ Membranes with larger pores (> 40 nm), might show limited performance, removing only large viruses or those attached to particles. The presence of pin-holes or small irregularities on the membrane surface might affect virus removal, as well. Some ultrafiltration systems are also applicable for turbid water where other systems clog or fail.

The number of ultrafiltration systems and products on the market is rapidly growing, but distribution is still mostly conducted through NGOs and projects. The filters are not yet freely available on the market in the majority of low- and middle-income countries.

Operation and maintenance

The layer of particles and microorganisms formed on the membrane surface during filtration is mostly removed by backflushing (flow of a small amount of clean water in the reverse direction) or cleaning (addition of chemicals, shaking, flushing the surface, etc.). If cleaning is not performed regularly, certain systems may clog. Training is needed to operate some of the products available on the market. Membrane filters need to be replaced when they are irreversibly clogged (so conducting standard cleaning leads to only a slight increase in flow), which is a good indicator of failure. Usually a failure-free operation of 1–2 years is guaranteed by the producer for rather turbid waters, and the filters can be operated longer with clear water. Most polyethersulfonate or polysulfone membranes on the market cannot be dried completely or they become irreversibly clogged, such as during storage. Thus, they should be kept wet or in moist environment during long standstill periods.

Health and environmental aspects/Acceptance

Membrane filtration is a simple and fast way of producing high-quality water. Since suspended particles are fully removed without changes in water taste and odour, treated water is usually perceived as safe and clean. When explained, people easily understand the principle of filtration. Some systems are not operationally self-explanatory, meaning proper training is needed for good uptake and appropriate use of the technology. Additionally, some systems produce concentrated retentate during backflushing, which has higher concentration of microorganisms than raw water and needs to be discharged properly. Backflushed water used in households for other needs can present a health risk.

The membrane field is developing quickly, and new products and technologies based on ultrafiltration appear on the market every year. Good quality control during manufacture is important to ensure reliable performance in the field.

+ Advantages

- Removes high level of bacteria and protozoa in high-quality products. Virus removal depends on the pore size of the membrane, with best results from dense, high-quality ultrafiltration membranes.
- Can handle turbid waters in many systems
- Usually light, small, and easy to transport; no damage during transport is expected
- Easy to operate and maintain when operation principle is understood

– Disadvantages

- Requires frequent cleaning (e.g. backflushing, flushing)
- Might include hand pumps with small parts that are subjected to damage
- Is not always intuitive to operate filters, and training is usually needed
- Clogs quickly when not operated properly
- Provides no residual disinfection (safe storage/handling must be practised post-treatment)

→ References and further reading materials can be found on page 219.

¹⁶ For product specific LRVs, refer to WHO's International Scheme to Evaluate Household Water Treatment Technologies: <https://www.who.int/tools/international-scheme-to-evaluate-household-water-treatment-technologies/products-evaluated>

H.4 Chemical disinfection

Applicable to systems
1, 2, 3, 4, 5, 6, 7

Management level
Household, school, health
center, neighborhood

Local availability of technology
or components
Yes

Technology maturity level
Established technology



Chemical disinfectants inactivate microorganisms by oxidizing their biochemical building blocks, thus disrupting vital cell functions. Chlorine is the most commonly used chemical disinfectant for drinking-water, although other oxidants such as bromine, iodine, and peroxide are available. The efficacy of chemical disinfectants depends on how reactive they are against specific microorganisms, their concentration and contact time, and water quality characteristics such as pH, oxidant demand, and temperature.¹⁷

Chlorine application at the household level may achieve a 3-6 log reduction value (LRV) for bacteria and viruses (WHO, 2022a). However, it is ineffective against microorganisms with strong cell walls, such as *Cryptosporidium* oocysts and some bacterial spores at concentrations and contact times practical for water treatment. It reacts rapidly with (in)organic compounds in water that exert a demand on the chlorine, thus influencing the concentration available for microbial disinfection. For treatment at the household level, chlorine is generally available in liquid form as hypochlorous acid (commercial household bleach or more dilute sodium hypochlorite solution), or in dry form as calcium hypochlorite or sodium dichloroisocyanurate (NaDCC).

The product information sheets need to be followed exactly to avoid under dosing (which may compromise

the microbiological safety of the water) or overdosing (which may impact the acceptability of the water in terms of taste and odour).

Turbidity can shield microorganisms from disinfection. Furthermore, high organic matter content in the water leads to the formation of disinfection by-products. This should be minimized due to the potential health concerns associated with long-term exposure to these compounds. However, the long-term potential risks to health from these by-products are low in comparison with the confirmed acute risks associated with inadequate disinfection, so disinfection should not be compromised in attempting to control disinfection by-products.

Applicability and adequacy

Disinfection using chlorine is relatively quick, simple, and cheap. Chemical disinfectants are appropriate for places where water is contaminated with bacteria. Chlorination has proven to be very efficient in emergency situations and as a response to cholera epidemics. In locations also affected by anthropogenic or geogenic contaminants or very high natural organic matter content, chlorination should be used along with other technologies.

Operation and maintenance

In some cases, the water will need to be pre-treated (e.g. by filtration or coagulation) to remove particulate

matter. Chlorine-containing chemicals should be stored in a cool, dry place, and care should be taken to keep the chemicals away from the eyes or clothing. Disinfection with chlorine is easy to learn and must be done regularly. Apart from cleaning and the occasional replacement of containers and utensils, no maintenance is needed.

Chlorination requires a constant supply of consumable chemicals that users must be willing and able to purchase regularly. Chlorine can be locally or regionally produced and is distributed in bottles that treat hundreds to thousands of litres before a repeat purchase is necessary. Chlorine tablets can be purchased in individual units or in multiple units (bottles and blister packs) that require regular or periodic repeat purchases.

Chlorine may degrade over time or if improperly stored. Liquid and solid chlorine should always be stored away from direct sunlight, excessive humidity, and high or varying temperature. Chlorine should be stored and used according to the manufacturer's guidelines and within the expiry date.

Health and environmental aspects/Acceptance

A constant supply of chlorine must be guaranteed for consistent use. Some users are reluctant to chlorinate due to the associated water taste and odour. User skepticism about chlorine effectiveness may arise from the unchanged appearance of the water after treatment (e.g. relative to other household technologies such as filtration, where improvements in water quality are visibly apparent). User education and awareness raising should be practised to communicate the health benefits of chlorine disinfection.

Chlorine products have to be handled carefully as they can irritate the skin, eyes, and respiratory system.

- May deteriorate over time and when stored inappropriately

→ References and further reading materials can be found on page 219.

⊕ Advantages

- Is easy to apply
- Is cheap and reliable
- Can inactivate most bacteria and viruses
- Provides residual disinfection which can provide some protection against low-level microbial recontamination and growth
- Is widely available in different countries

⊖ Disadvantages

- Must be continuously purchased
- Users may object to taste and odour
- Has product-specific dose requirement (depending on product concentration)
- Requires clear water (ideally turbidity < 5 NTU) to be most effective
- Has restricted availability in rural or remote areas
- Ineffective against several protozoa including *Cryptosporidium* oocysts

17 For product specific LRVs, refer to WHO's International Scheme to Evaluate Household Water Treatment Technologies:
<https://www.who.int/tools/international-scheme-to-evaluate-household-water-treatment-technologies/products-evaluated>

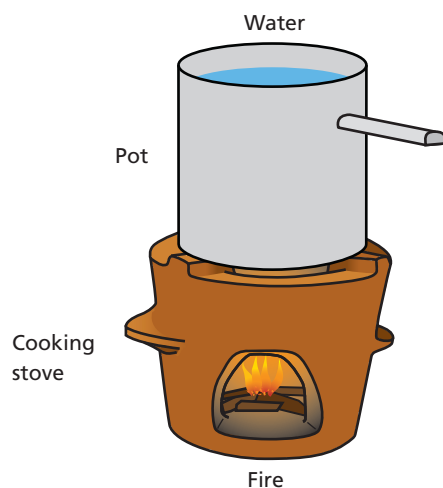
H.5 Boiling

Applicable to systems
1, 2, 3, 4, 5, 6, 7

Management level
Household

Local availability of technology
or components
Yes

Technology maturity level
Established technology



Boiling water with fuel is the oldest and most commonly used method worldwide for treating small quantities of water used at the household level. Boiling water inactivates all microorganisms including bacteria, protozoa, and viruses, but does not remove turbidity or chemical contaminants from drinking-water.

Microorganism inactivation already occurs below the standard boiling point of 100°C. Most bacteria, viruses, and protozoa are inactivated in less than 1 minute once temperatures exceed 70°C. Boiling can achieve > 9 log reduction value (LRV) for vegetative cells, noting that spores may be more resistant (WHO, 2022a). However, the appearance of bubbles is a good visual indicator, and thus it is recommended to heat water to a rolling boil. To avoid recontamination, water should be stored in a clean and covered container after boiling (see H.1 Storage tanks or reservoirs). Water should be handled carefully and no utensils should be brought in contact with the water when pouring into a clean container for consumption.

Since boiling requires a heat source, rudimentary or non-conventional methods of heat generation may be needed in areas where electricity or fuels are not available. Despite its effectiveness and simplicity, boiling requires affordable and sufficient fuel to produce adequate quantities of boiled water for regular drinking purposes and can be quite labor-intensive.

Applicability and adequacy

Boiling is suitable where sufficient fuel sources (e.g. wood, kerosene, electricity, gas, charcoal, etc.) are locally available when needed and at an affordable cost. In general, the long-term cost of boiling is greater than other alternatives, and when the availability and cost of fuel are limited, boiling might not be done consistently. Boiled water tastes flat, which may impact consumer acceptance. The taste might be improved by cooling.

Water containing high amounts of iron and calcium will deposit white scales at the bottom of the container used for boiling. In such cases, the container should be washed properly after each use.

Operation and maintenance

When fuel has to be collected or treated, this can occupy much of a household's time. At the kitchen level, everyday maintenance includes checking the stove and pots. The frequency with which the stove will need to be repaired or replaced will depend on stove design, the quality of materials and workmanship, and the intensity of use. Pots are seldom repaired, and earthen pots often need to be replaced. The necessary skills for operation and maintenance activities are usually available in all communities.

If turbid water needs to be clarified for aesthetic reasons, this should be done before boiling to avoid recontamination.

Health and environmental aspects/Acceptance

In many places, it is an ingrained cultural practice to boil water for drinking, and the acceptance of this method is very high. The water is consumed in the form of drinks using boiled water as a basis, such as tea or coffee, to mask the changed taste. The method can be used in combination with other technologies, where water is boiled for hot drinks, but another treatment method is used for direct consumption.

Since boiling does not provide residual protection from microbial recontamination, water that is not consumed within a short time after boiling should be protected by using of safe water storage practices.

Despite the extensive use of this method, boiling can cause health issues that may limit its scalability as a means of routinely treating water. Boiled water may cause burn injuries if not handled properly. Children should not be responsible for boiling water on their own, and boiling water should be placed out of their reach to avoid the risks of burns. The person boiling the water may suffer from the associated respiratory diseases caused by long-term exposure to fire or stove smoke. Therefore, indoor cooking spaces should be well ventilated.

Depending on the fuel used, this method may be environmentally unsustainable and contribute to greenhouse gas emissions. Especially in densely populated areas, boiling with fuelwood contributes to the overexploitation of wood resources and the subsequent environmental damage, such as desertification and soil erosion.

→ References and further reading materials can be found on page 219 and 220.

⊕ Advantages

- Effectively inactivates pathogenic microorganisms of all classes
- Is an easy, simple, and widely culturally accepted method of disinfection
- Biogas cooking stoves can be used for boiling

⊖ Disadvantages

- Can be expensive due to high fuel consumption
- Contributes to indoor air pollution and deforestation issues where traditional fuel is used (e.g. firewood, gas)
- Does not remove turbidity, chemicals, taste, smell, or colour
- Provides no residual disinfection (safe storage/handling must be practised post-treatment)
- Is time consuming
- Requires cooling time before use, except for hot drinks
- Has a risk of burns and injuries

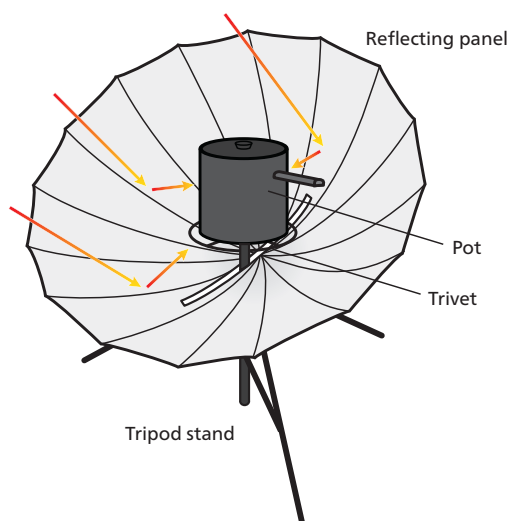
H.6 Pasteurization

Applicable to systems
1, 2, 3, 5, 6, 7

Management level
Household, neighborhood

Local availability of technology or components
Yes; some key parts may be only regionally available (i.e. thermostatic valve, indicators, etc.)

Technology maturity level
Established technology



Water pasteurization uses heat to inactivate pathogenic microorganisms. In practice, it is recommended to hold water at 70 °C for 15 minutes.

Water pasteurization can be referred to as solar cooking, which is one of its main applications at the household scale. Solar cooking uses a mirrored surface with high regular reflectivity to concentrate the energy of direct sunlight onto a cooking pan. The cooking pan is produced out of materials that conduct well and retain heat, which are often black or dark in colour. A lid helps to avoid heat loss. A glass lid might further increase the efficiency by creating a glasshouse effect, though in general, any metal pot covered with lid or even plastic bag can be used.

Besides solar cooking, other forms of heat can be used for pasteurization at a household scale, such as open fire and waste heat from cooking meals. With open fire, water is passed through a metal tube installed around the cooking stove or flows through a short tube placed in an open fire.

Pasteurization can achieve high log reduction values (LRVs) at 60–70 °C for exposure times of less than 1 minute. However, bacterial spores and protozoan cysts representing early stages in the life-cycle of some microorganisms can be more resistant to thermal inactivation. To significantly reduce spores, a sufficient temperature and time must be ensured, usually corresponding to a temperature of 70 °C for at least 15

minutes.

Applicability and adequacy

Household devices are usually very low-cost and can be manufactured locally. Solar cookers are also used for cooking meals, making them more attractive.

For the proper use of household devices, only basic initial training is recommended. Treated water should be stored in safe water storage devices (see H.1 Storage tanks or reservoirs) to prevent microbial recontamination and growth.

Operation and maintenance

Unlike boiling, where the recommendation is to bring water to a rolling boil, there is no visual natural indicator for water pasteurization. Therefore, some products on the market were designed for this purpose, such as thermostatic valves that only dispense water when the pasteurization temperature has been reached. There are also indicators made of a transparent plastic tube partially filled with wax that melts at 70 °C, which indicates that the pasteurization conditions were reached when the wax melts. Suitable bottles/vessels/jerrycans are also required. Most of them incorporate some type of window for solar irradiation, which must be cleaned regularly, and need to be exchanged when they lose their transparency.

For solar cooking, the solar collector surface must be cleaned daily. Cleaning can be done using a broom, brush or cloth, but scratching of the surface must be

avoided.

Due to the comparably low output and high vulnerability to cloudy weather, good planning is important and sufficient storage capacity is required.

Health and environmental aspects/Acceptance

Burn injuries from hot surfaces are the major threat to human health while handling solar cookers or using other pasteurization techniques. Children should not use solar cookers or other pasteurization equipment on their own, and the operating equipment should be placed out of reach of children when possible to avoid the risk of burns. If fire or fuel are used for pasteurization, long term exposure to smoke may cause associated respiratory diseases. Therefore, indoor cooking spaces should be well ventilated.

Since pasteurization does not provide residual protection from microbial recontamination, water should be protected by using safe water storages.

⊕ Advantages

- Has almost no treatment costs
- Can use multiple energy sources
- Only requires suitable containers and any heat source (solar power)

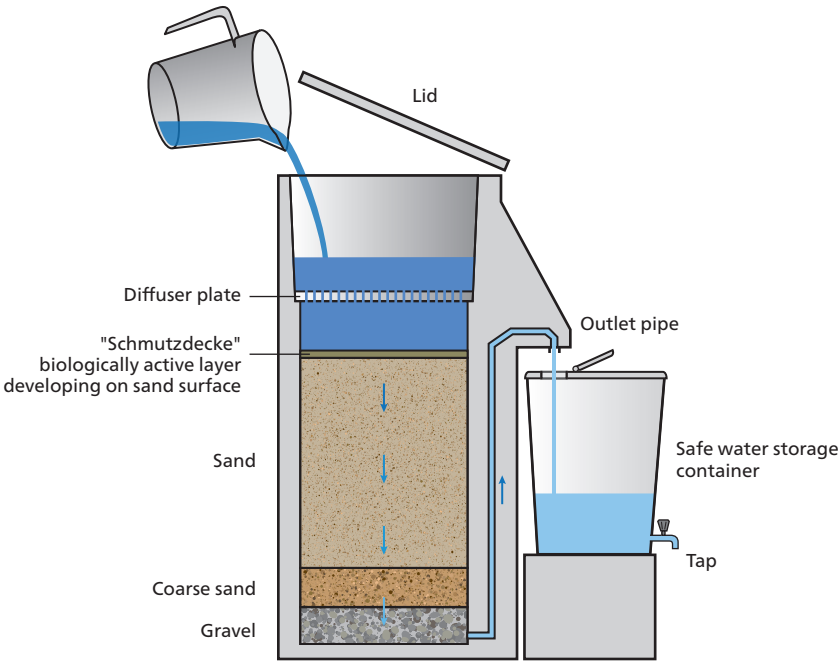
⊖ Disadvantages

- Has relatively small treatment capacity
 - Creates unpleasant, warm water after treatment
 - Is vulnerable to unstable weather if solar powered – clouds, rain, and polar regions limit efficiency
 - Provides no residual disinfection (safe storage/handling must be practised post-treatment)
 - Does not remove turbidity, chemical pollutants, taste and colour
-

→ References and further reading materials can be found on page 220.

H.7 Biosand filtration

Applicable to systems 1, 2, 3, 4, 5, 6, 7	Management level Household, school, health center, neighborhood, small community	Local availability of technology or components Yes	Technology maturity level Established technology
---	--	--	--



A biosand filter (BSF) is a simple device based on the slow sand filter concept that is designed for intermittent use in households or small communities. A biosand filter is a concrete or plastic container filled with specially selected sand and gravel. The removal of pathogenic microorganisms occurs through a combination of physical trapping and biological processes in a “Schmutzdecke” – the biofilm layer formed in the top layers of the filter.

The filter container is made of water-proof, rust-proof and non-toxic material, such as concrete, plastic, or ceramic pot. The most common version is a concrete container about 0.9m high with a surface of 0.3m². The container is filled with layers of washed and sieved sand and gravel. The filter media is arranged in the container such that the material with the thinnest granularity (sand) is on top and the coarser material is at the bottom (gravel of different sizes to support filtration sand and prevent it from moving down the drainage). The untreated water is poured into the top of the container and flows through all filtration layers by gravity. The outlet pipe height maintains about

5 cm of water above the sand level to ensure the ideal conditions for biofilm development and prevent filter drying. The biofilm on the sand surface is protected by a diffusion layer that slows the water flow and keeps the biofilm intact. This can be a plate with small holes drilled in it. Clean water is collected at the outlet pipe and can be consumed directly or stored afterwards in an external safe water storage container.

Applicability and adequacy

A biosand filter is suitable for drinking-water treatment for households, schools, or small communities (flow rates over 30 L/h can be achieved). Groundwater and surface water can be used. These filters reduce turbidity, organic matter content, microorganisms, oxidized iron, and manganese. Up to 4 log reduction value (LRV) can be achieved for protozoa. The removal of bacteria and viruses depends on the operational conditions (including flow rate, temperature and filter contact time), filter maturity, grain size, and raw water composition, with optimal conditions achieving up to 2 LRV for viruses and up to 3 LRV for bacteria (WHO, 2022a).¹⁸ Due to the limited pathogen removal, post-disinfection is recommended (e.g. H.4 Chemical

disinfection, H.6 Pasteurization, H.8 Ultraviolet (UV) light disinfection, H.9 Solar water disinfection).

Due to the partial removal of total organic carbon, the biological stability of the water increases, reducing the risk of microbial regrowth. Biosand filters should not be used for waters with turbidity exceeding 50 NTU, as they will clog quickly.

Biosand filters can be constructed locally with appropriate training. Locally available containers such as plastic barrels, tanks, and ceramic pots can be redesigned as biosand filters, or the housing can be made out of concrete. The selection and correct preparation of the filtration sand and gravel is crucial for treatment. Poorly chosen and prepared filtration materials lead to low treatment performance. Crushed rock should be used whenever possible. Otherwise, river or beach sand can be used, but are not recommended. If used, they should be washed to remove organic matter, microbial contamination, and salts; disinfected; and dried well before sieving.

Operation and maintenance

It takes between 20 and 30 days for the biological layer of the filter to fully mature, which depends on the inflow water quality and usage, among other factors. Therefore, the initial removal efficiency of the biosand filter is quite low until an acceptable level of the microorganisms develops (usually 2–3 weeks).

Over time, the flow rate through the filter will be reduced as the pore openings between the sand grains become clogged. When the flow rate reaches a critically low level (after several months, if the turbidity is lower than 30 NTU), the filter needs to be cleaned. A swirl and dump process is performed by agitating the surface sand and then removing the standing water containing suspended material. This standing water should not be disposed of in an open environment, as it might pose a health risk. After cleaning, the biological layer takes some time to recover its efficiency level, though it is quicker than for the first use.

Health and environmental aspects/Acceptance

A biosand filter is generally well accepted, especially with the visual improvement of water clarity and colour when turbid surface water is used as the source. However, depending on operation and maintenance practices, filters might remove only a limited amount of pathogenic microorganisms. Water at the outlet pipe can be easily recontaminated, so treated water should be collected by the user in a safe storage container (H.1 Storage tanks or reservoirs) placed just under the outlet, and should be further disinfected as required (H.4 Chemical disinfection, H.6 Pasteurization, H.8 Ultraviolet (UV) light disinfection, H.9 Solar water disinfection).

+ Advantages

- Has high user acceptability (easy to use, improves look and taste of water)
- Produced from local materials
- Has one-time installation with low maintenance requirements (no chemicals, no energy)
- Has a long lifespan

– Disadvantages

- Provides no residual disinfection (safe storage/handling must be practised post-treatment)
- Requires regular use and takes time to develop the biological layer to maturity (20–30 days)
- Loses efficiency in cold temperatures
- Has risk of clogging with highly turbid waters
- Is difficult to transport and initial cost might be high.

→ References and further reading materials can be found on page 220.

18 For product specific LRVs, refer to WHO's International Scheme to Evaluate Household Water Treatment Technologies: <https://www.who.int/tools/international-scheme-to-evaluate-household-water-treatment-technologies/products-evaluated>

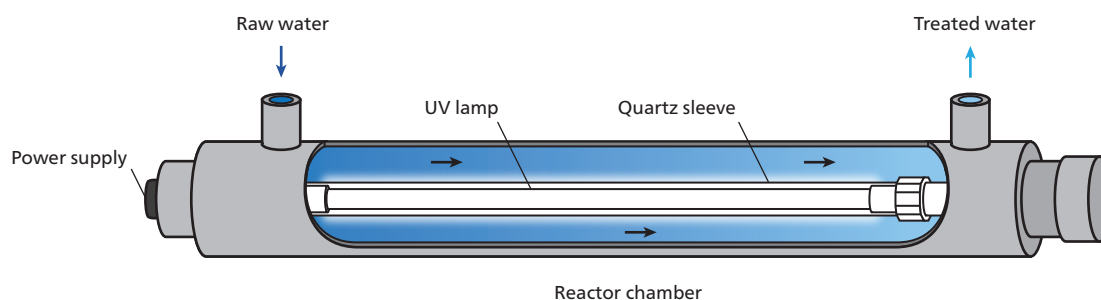
H.8 Ultraviolet (UV) light disinfection

Applicable to systems
4 (1, 2, 3, 5, 6)

Management level
Household, school, health center, neighborhood, small community

Local availability of technology or components
Sometimes

Technology maturity level
Established technology



UV light is a non-chemical approach for disinfecting water. It is effective against all classes of pathogens and requires only seconds of contact time. It has been successfully used for drinking-water treatment at the household scale.

The UV irradiation used in water treatment is generated from mercury lamps or from UV light emitting diodes (LEDs). UV disinfection is a physical process where emitted photons are absorbed by and damage critical cellular components, such as nucleic acids (DNA and RNA) and proteins, which inhibits normal cellular function and is eventually lethal. As DNA and proteins absorb light in the 200–300 nm range, these are the optimal disinfection wavelengths, with 250–270 nm being the ideal range. Some bacteria are able to repair DNA damage, especially when exposed to the wavelengths present in sunlight, if the radiation received was not sufficient.

For household drinking-water treatment with UV irradiation, low pressure mercury vapor lamps are typically applied, which emit a single peak of UV radiation at 254 nm. UV-emitting LEDs are rapidly gaining popularity, specifically for point-of-entry and point-of-use at low flow rates in households. UV LEDs can be designed for different emission outputs and are typically used at 255–285 nm.

Typical point-of-entry or point-of-use UV disinfection systems include a single UV lamp encased in a quartz sleeve and either submerged in a closed conduit system

or placed above a free water surface. UV systems are usually made of stainless steel, UV-reflecting Teflon, or plastic sleeves. When UV LEDs are used, there is typically an array of LEDs encased in a reflective chamber behind a quartz plate, and water is irradiated as it flows through the chamber.

Water flows across the lamps from one end of a UV system to the other in a matter of seconds and is disinfected. To provide the proper UV dose to inactivate all pathogenic microorganisms, the hydraulic retention time in the system must be carefully considered to ensure sufficient UV radiation exposure time and lamp output intensity. Water quality, specifically the UV transmittance of the water, is a key design parameter.

A typical low-dose UV treatment ($1\text{--}10\text{ mJ/cm}^2$) achieves at least a 3 log reduction value (LRV) for vegetative bacteria and protozoan parasites, including *Cryptosporidium parvum* and *Giardia lamblia* (depending on delivered fluence [dose], which varies with intensity, exposure time, and UV wavelength as well as turbidity and presence of certain dissolved solutes, and general operation and maintenance conditions [WHO, 2022a]).¹⁹ To inactivate enteric viruses and bacterial spores, higher doses ($30\text{--}150\text{ mJ/cm}^2$) are required. The UV dose for water disinfection is usually designed for $25\text{--}40\text{ mJ/cm}^2$. Only validated UV systems providing the designed dose under typical flow rates and UV transmittance values should be used. UV transmittance at 254 nm of drinking-water sources is typically greater than 80%.

Other water quality parameters, such as turbidity or suspended solids, can reduce the disinfection efficiency by shielding the pathogen targets from the light. Inorganic constituents, such as iron or manganese, can foul the lamp and reduce light transmission. Ideally, the turbidity is <5 NTU and the transmittance >70% at 254 nm over a 1 cm pathlength. Pretreatment, such as filtration or activated carbon depending on the composition of the raw water, may be desired when water-quality parameters do not meet the limiting thresholds.

Applicability and adequacy

UV lamps require a continuous power supply either from conventional electricity or solar or mechanical means. Ideally, the intensity status and expected remaining lifetime should be monitored by a UV sensor and a lamp-status on/off indicator. UV disinfection does not protect from microbial recontamination and regrowth after treatment. UV irradiation is not suitable for eliminating physical or chemical pollutants.

Operation and maintenance

For household and small-scale systems, daily operation includes switching on the lamp when water needs to be treated. An indication of the lamp status should be noted. If an intensity sensor is present, the operating lamp intensity can be tracked to determine when it falls below a set-point for validated performance (approximately 70% or less from initial design value). Regular maintenance of the system includes flushing debris from the reactor and wiping the quartz sleeve with a soft cloth (to avoid scratching) and slightly acidic solution to remove any fouling material that may have been deposited. Feed water quality should be checked periodically for UV 254 nm transmittance and turbidity and only used when within the validated range of the UV system. If necessary, pretreatment should be used to ensure UV disinfection effectiveness. UV mercury lamps usually reach their end of life after 8,000 operating hours and should be replaced at this time to ensure proper disinfection. For LEDs, the lifespan varies depending on the specifications and manufacturer. At least yearly, the inner surface of the reactor should be inspected and cleaned.

Health and environmental aspects/Acceptance

Direct exposure to UV radiation must be avoided, as it can burn the skin and damage the eyes. Therefore, users must protect their eyes and skin during maintenance and operation. Because of the lack of residual disinfectant, treated water should be stored safely. If the mercury lamp breaks, toxic mercury may be released, potentially harming the operator or the environment.

+ Advantages

- Operates simply and inexpensively
- Does not require supply of chemicals
- Does not change taste or odour of the water
- Less potential to form disinfection by-products
- Inactivates microorganisms with high chlorine-resistance, such as *C. parvum* oocysts

- Disadvantages

- Requires reliable power supply
- Requires some spare parts (mercury lamp)
- Does not have residual disinfectant (safe storage must be otherwise assured)
- Requires pretreatment for turbid and low transmittance waters

→ References and further reading materials can be found on page 220.

19 For product specific LRVs, refer to WHO's International Scheme to Evaluate Household Water Treatment Technologies:
<https://www.who.int/tools/international-scheme-to-evaluate-household-water-treatment-technologies/products-evaluated>

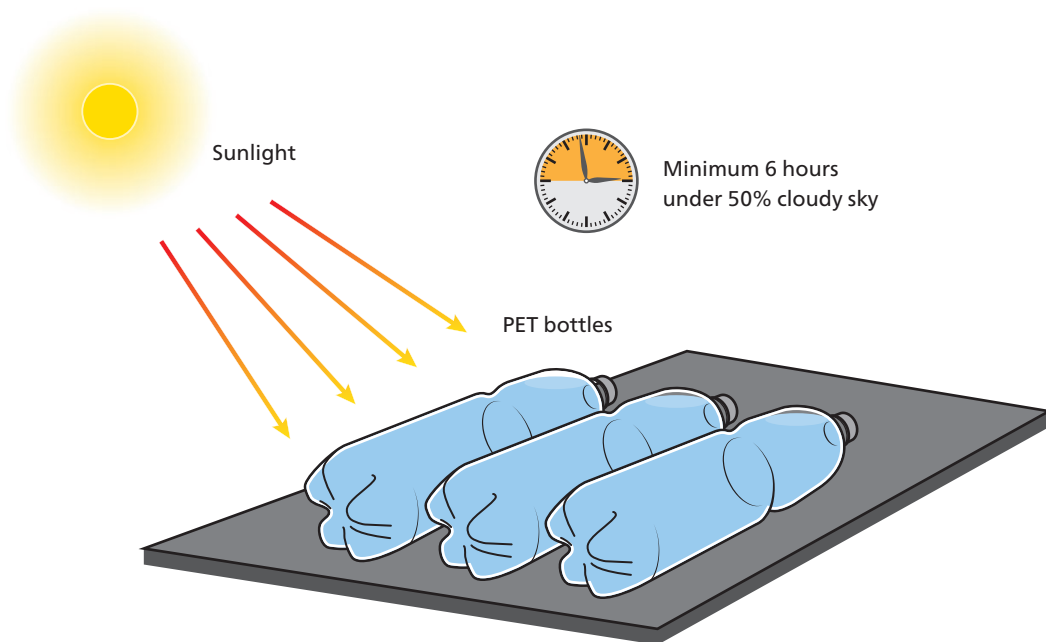
H.9 Solar water disinfection

Applicable to systems
4 (1, 2, 3, 5, 6)

Management level
Household

Local availability of technology
or components
Yes

Technology maturity level
Established technology



Solar disinfection inactivates microorganisms through a combination of UV irradiation, visible light radiation, and heat. This is a simple and low-cost household water treatment method.

UV irradiation damages nucleic acids, thus impairing their replication, and photosensitive molecules in the water absorb visible light, resulting in oxidation that damages cellular structures. The exposure to sunlight also increases the temperature, which denatures proteins within the microorganisms and/or causes oxidative damage associated with dissolved oxygen products and heat. The effectiveness of solar disinfection depends on the sun's intensity, which is affected by weather conditions and geographical location. Solar disinfection is most effective in tropical or subtropical regions of up to 35 degrees latitude.

A variety of solar disinfection technologies are available, including dark/opaque containers that rely on heat from sunlight to disinfect water; clear polyethylene terephthalate (PET) containers that rely on the combined action of UV radiation, oxidative activity associated with dissolved oxygen, and heat (also known as SODIS); or combinations of these effects in other types of containers, such as UV-penetrable bags and panels.

Solar disinfection operated under optimal conditions can provide >5 log reduction value (LRV) for bacteria, and >4 LRV for viruses and protozoa. However, these values may vary depending on oxygenation, sunlight intensity, exposure time, temperature, turbidity, and the size of water vessel (i.e. depth of water; WHO, 2022a).²⁰

Solar disinfection does not reduce chemical contamination in water (e.g. arsenic, fluoride, or industrial and agricultural organic contaminants).

Applicability and adequacy

The penetration of UV radiation is reduced at increasing water depths. Therefore, the containers used for solar disinfection should not exceed a water depth of around 10 cm. Usually containers of a volume of up to 3 L are used. The containers should not be shaded by trees, houses, or other objects. In general, high turbidity can impact the efficacy of solar disinfection. In the case of SODIS, turbidity >30 NTU requires pretreatment by clarification methods (H.2 Ceramic filtration, H.3 Ultrafiltration, H.7 Biosand filtration).

Operation and maintenance

Operation primarily requires time, proper planning of daily water needs (e.g. during prolonged exposure to sunlight on cloudy days), and good weather conditions.

No special technical knowledge is required. The user must ensure that damaged or scratched containers are replaced and that there is a sufficient supply with appropriate containers. When commercially available containers, such as PET bottles, are reused, the bottles should be washed well and all plastics or paper labels should be removed.

The exposure time varies depending on the sunlight available. For example, PET bottles (SODIS method) need to be exposed for at least 6 hours under 50% cloudy sky. On days of continuous rainfall, solar disinfection should not be used. Some systems have indicators showing exposure time or temperature. The treated water should be stored in the disinfection bottles until consumption to avoid recontamination. It is recommended that treated water be consumed within 24 hours.

Health and environmental aspects/Acceptance

The regular daily application of solar disinfection requires time and effort. A comprehensive behaviour change intervention, involving careful interpersonal training and supervision, is required to establish a regular and consistent practice of water treatment. Overall, the sustainability of solar disinfection appears to be variable and may depend on the quality of the implemented behavioural change process.

After their useful lifetime, plastic bottles or bags should be collected and sent to a proper disposal facility (e.g. recycling, incineration, or landfill).

⊕ Advantages

- Inactivates bacteria effectively; inactivation of viruses and protozoa depends on several factors, including temperature and exposure time
- Has very low treatment costs
- Does not require power supply
- Does not affect water taste
- Protects against recontamination if the water is stored in the PET bottles until consumption

⊖ Disadvantages

- Has long treatment time and low treatment capacity
 - Is vulnerable to unstable weather
 - Depends on access to sufficient amount of PET bottles or other suitable containers
-

→ References and further reading materials can be found on pages 220 and 221.

20 For product specific LRVs, refer to WHO's International Scheme to Evaluate Household Water Treatment Technologies:
<https://www.who.int/tools/international-scheme-to-evaluate-household-water-treatment-technologies/products-evaluated>

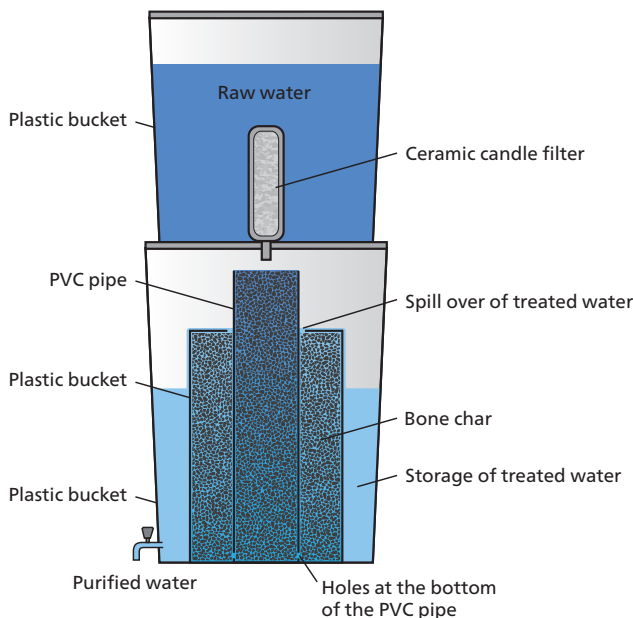
H.10 Fluoride removal filters

Applicable to systems
4, 7

Management level
Household

Local availability of technology
or components
Mostly (not always for the adsorption
media)

Technology maturity level
Established technology



Fluoride is a groundwater contaminant from geogenic sources, such as the minerals present in rocks and soils.²¹ Fluoride can be removed from groundwater by adsorption on calcium-phosphate- or aluminum-oxide-based filter materials, or by precipitation and coagulation treatment processes.

Fluoride is an essential building block for the formation of tooth enamel and bones, which is why municipal drinking-water supplies in some regions are artificially fluoridated. On the other hand, the consumption of drinking-water with too much fluoride over a long period can degrade teeth and bones. The WHO guideline value for fluoride in drinking water is 1.5 mg/L (WHO, 2022a).

Community-scale fluoride removal techniques (see T.3.1 Fluoride removal methods) can also be applied on a household scale. Generally speaking, centralized treatment is preferred, as fluoride removal efficiency, water quality, and maintenance activities can be more easily monitored there than in individual households. Nevertheless, household treatment may be the only option in some cases. In low-income countries, low-cost fluoride removal techniques rely on precipitation and coagulation or adsorption/ion-exchange processes.

Precipitation/coagulation: By adding chemicals such as calcium and aluminum salts, precipitates form that bind fluoride and can be removed by conventional sedimentation and filtration steps. The Nalgonda technique, for example, uses aluminum sulphate and calcium hydroxide (lime) as coagulants. Other techniques include electrocoagulation and the Nakuru technique, the latter being a mixture of precipitation and adsorption processes.

Adsorption and ion exchange: Fluoride-contaminated water is passed through a layer of porous material (contact bed), which removes fluoride by ion exchange or adsorption to the contact bed material. Appropriate contact bed materials include activated alumina or calcium-phosphate-based materials, such as synthetic hydroxyapatite and bone char. An important advantage of adsorption techniques is that many filter materials can be regenerated. When the uptake capacity is reached, fluoride is removed from the filter by passing a basic solution over the filter bed, followed by an acidic solution for reactivation. The filter media can then be reused for further fluoride removal.

Applicability and adequacy

Techniques requiring the daily addition of chemicals for fluoride coagulation and precipitation (e.g. Nalgonda technique) are not very practical on a house-

hold level, as the daily operation (chemical dosing, stirring, settling, sludge removal) is time consuming and error-prone. Filtration methods are therefore preferred for household systems. The amount of water filtered by such systems is usually in the range of 20–40 L/day.

For filtration on a household level, it is important to calculate the predicted time of filter saturation based on the uptake capacity of the material, the fluoride concentration of raw water, and the amount of water filtered per day. In this way, fluoride in the treated water can be analysed by the filter distributor when approaching the point of saturation, and the material can be replaced or regenerated when necessary. Regeneration will need to be organized off-site and performed by trained staff (handling of acids and bases). The fluoride removal capacity is reduced after each regeneration cycle.

Operation and maintenance

The operation of household fluoride removal filter systems is generally simple for water users. The necessary contact time between the water and filter bed, which differs depending on the filter material, should be respected to ensure efficient fluoride removal. Regular water quality monitoring, replacement, and/or material regeneration should be organized by the distributor/vendor of the filters and relies on user cooperation.

Health and environmental aspects/Acceptance

Bone char may not be acceptable in some areas for religious or cultural reasons. The sludge generated daily using the Nalgonda technique needs to be carefully disposed of. This technology does not remove microbiological contamination. There is also a risk of water contamination due to poor hygiene practices, so post-filtration (H.2 Ceramic filtration, H.3 Ultrafiltration) or post-disinfection (H.4 Chemical disinfection, H.5 Boiling, H.6 Pasteurization, H.8 Ultraviolet (UV) light disinfection, H.9 Solar water disinfection) might be required. Treated water must always be stored in safe water storage containers (H.1 Storage tanks or reservoirs).

Nalgonda technology:

⊕ Advantages

- Uses readily available chemicals
- Is low-cost

⊖ Disadvantages

- Is complicated and time consuming for household use
- Has moderate fluoride removal capacity
- Requires disposal of fluoride precipitate

Activated alumina:

⊕ Advantages

- Has high fluoride uptake capacity
- Is easy to use
- Can be regenerated

⊖ Disadvantages

- Requires off-site regeneration
- Requires relatively expensive materials

Bone char:

⊕ Advantages

- Is easy to use
- Is low-cost
- Can be regenerated

⊖ Disadvantages

- Requires off-site regeneration
- Has low to moderate fluoride uptake capacity; frequent water quality monitoring necessary

→ References and further reading materials can be found on page 221.

21 See risk maps showing regions with a high likelihood of elevated fluoride concentration in groundwater: <https://www.gapmaps.info>

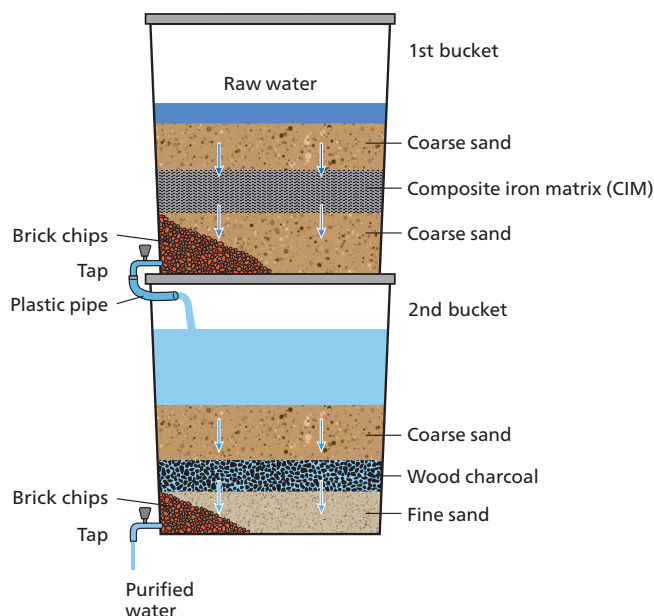
H.11 Arsenic removal filters

Applicable to systems
4, 7

Management level
Household

Local availability of technology
or components
Mostly (not always for the adsorption
media)

Technology maturity level
Established technology



Arsenic is a groundwater contaminant originating from geogenic sources, such as the natural minerals present in rocks and soils.²² Arsenic can be removed from groundwater by precipitation, adsorption, ion exchange processes, or reverse osmosis.

Arsenic in groundwater can derive from natural sources, such as rocks and soil, as well as from industrial activities like mining. Several regions of the world are severely affected by arsenic in groundwater. The consumption of water that is contaminated with arsenic over a period of time can result in chronic arsenic poisoning. Long-term exposure to arsenic can change the pigmentation of the skin and increases the risks of various cancers and other diseases, including those related to the lung and heart. The WHO guideline value for arsenic is 10 µg/L, which is provisional on the basis of the difficulties with removing arsenic to lower levels using conventional water treatment (WHO, 2022a).

In the environment, arsenic occurs in pentavalent (As V) and trivalent (As III) forms; the prevailing form depends mainly on the surrounding redox conditions. In groundwater, trivalent arsenic is often found, which is not as easily removed as pentavalent arsenic. Pentavalent arsenic (As V) is strongly sorbed to various solids, such as trivalent iron oxides. Therefore, a

pre-oxidation step of trivalent arsenic (As III) by ozone or chemicals is recommended to form pentavalent arsenic (As V) prior to water treatment.

Several household filter designs with different removal processes are commercially available. Most systems are composed of two buckets/compartments, where trivalent arsenic (As III) is oxidized to pentavalent arsenic (As V) in the first bucket, and pentavalent arsenic is removed by precipitation or by adsorption on a pre-fabricated commercial adsorbent in the second bucket. One type of arsenic removal filter, widespread in Bangladesh, is called SONO. SONO filters combine the oxidation of trivalent As(III) and sorption of pentavalent As(V) in a composite iron matrix consisting of iron scraps that produce a new adsorbent by the continuing corrosion of iron. In a second bucket, the remaining precipitated iron(III) arsenic is removed by filtration through sand and activated carbon layers.

Applicability and adequacy

The amount of water filtered by household systems ranges between 20–60 L/day. Removal efficiencies of arsenic depend on the design and components of the filter, but are in the range of 85–99%. Household arsenic removal filters are low-cost technologies that are simple to operate and use locally available materials and chemicals.

Operation and maintenance

The operation of arsenic filters is simple and includes daily filling of the water. The necessary contact time between the water and filter bed, which differs depending on the filter design and material used, should be respected to ensure efficient arsenic removal. Maintenance activities include periodic cleaning/flushing, disinfection, and the exchange of sand, activated carbon, or iron elements in the filters. Regular water quality monitoring and maintenance should be supported by the filter distributor/vendor and relies on user cooperation.

Health and environmental aspects/Acceptance

Arsenic-rich waste is produced by the filter systems, which has to be disposed of properly due to the high toxicity. The arsenic filters do not remove microbial contamination. There is a risk of water contamination due to poor hygiene practices, so post-filtration (H.2 Ceramic filtration, H.3 Ultrafiltration) or post-disinfection (H.4 Chemical disinfection, H.5 Boiling, H.6 Pasteurization, H.8 Ultraviolet (UV) light disinfection, H.9 Solar water disinfection) might be required. Treated water must always be stored within the filter or in a safe water storage container (H.1 Storage tanks or reservoirs). When ion-exchange resins are used, the raw water quality needs to be carefully considered. Other ions with a stronger affinity for the resin can displace pentavalent arsenic, leading to the uncontrolled release of large quantities of arsenic into the treated water.

⊕ Advantages

- Is relatively inexpensive and easy to use
- Uses locally available materials

⊖ Disadvantages

- Has varying arsenic removal efficiencies
 - Is not ideal for anion-rich water (e.g. sulphate and phosphate are competing ions)
 - Not used regularly by all users
-

→ References and further reading materials can be found on page 221.

²² See risk maps showing regions with a high likelihood of elevated arsenic concentration in groundwater: <https://www.gapmaps.info>

Part 3 | Cross-cutting issues

Implementing an effective and sustainable water supply system depends on not only technology selection, but also on factors such as planning, management, monitoring, maintenance, and the availability of external support. Specific local considerations, such as gendered divisions of labor or users' willingness to pay for safe water, play an important role in determining if water supply systems continue to function over the long-term. A strong policy and regulatory enabling environment is important to support sustainable water supply system management. The financial stability of a water system may be threatened by the availability of alternative freshwater sources, especially during the rainy months when use of the system is usually lowest. The functionality of water systems in remote rural areas is a particular challenge due to dispersed populations, limited technical expertise, and a lack of material supply chains. Resilience to future emergencies and disasters, including those arising from climate variability and change, must also be considered when planning water supply systems. Part 3: Cross-cutting issues introduces topics relevant to the planning, operation, and management of water supply systems to support their long-term effectiveness.

Project planning and implementation

X.1 Management typologies

X.2 Gender and inclusion

X.3 Life-cycle and environmental impact assessment

Assessing and managing risks

X.4 Risk assessment and risk management

X.5 Water safety planning

X.6 Sanitary inspections

X.7 Quantitative microbial risk assessment

Monitoring and service sustainability

X.8 Drinking-water quality regulation

X.9 Water quality monitoring

X.10 Data flow and information and communication technology (ICT)

X.11 External support programmes

X.12 Strengthening resilience to climate change

X.1 Management typologies

Drinking-water supply systems must be managed to ensure an adequate and safe supply. Management approaches can be broadly categorized as household, community-led, or professionalized. The approach best suited to a water supply system depends on its design, intended use, and the local availability of resources.

Water supply systems can be categorized as centralized (such as large urban piped networks), decentralized (such as boreholes equipped with hand pumps), or a combination of both. This fact sheet describes the management typologies applicable to these system designs, along with relevant enabling factors (Fig. 1).

Household managed

Household management refers to households being responsible for managing their own water supplies. This approach is most common in single or small groups of households living in remote rural or highly dispersed areas, where the costs of extending piped networks is prohibitively high. In these instances, decentralized, non-networked solutions are necessary, e.g. protected dug well (I.5 Protected dug well), roof water collection system (I.1 Roof water collection system), and protected borehole (I.6 Protected borehole). Households are responsible for most or all of the costs of construction, operation, and repairs, though a portion of these costs may be covered through government subsidies or local NGOs (called “supported” or “accelerated” self-supply).

In Bangladesh, household management has become the mainstream approach, where most of the rural population relies on protected dug wells financed in full by one or more families (Danert, 2015). In Ethiopia, household management was formally endorsed by the national government in 2012 as “a service delivery mechanism for rural water ... to reach more than 30% of citizens without safe water access” (Sutton et al., 2012). In the USA over 20% of the rural population relies on household management with private wells, and this percentage is as high as 60% for countries in Eastern Europe (Sutton, 2009).

Community managed

Community management is another demand-responsive approach that requires community members (e.g. a water user association or other community organization) to operate, maintain, and manage their own water supply system on a day-to-day basis. This management model typically involves a cost-sharing arrangement whereby an external government agency covers most construction costs and the community organization then adopts responsibility for the ongoing operation,

maintenance, and management costs. Community-based management models represent a broad spectrum, ranging from limited to advanced. Community organizations operating and managing the water supply may be untrained or undertrained and unpaid (i.e. volunteers). Since community managed water supply systems are often larger and more complex than self-supply systems, this management model relies on participatory planning, establishing water user committees, and capacity building through training and education (Schouten & Moriarty, 2003).

Community managed supplies may lack legal recognition, operate in the absence of accountability structures and the associated technical and financial supports (WHO, 2024b).

Community managed water supplies became the norm in many rural communities and small towns by the end of the 20th century, especially in sub-Saharan Africa where this management model remains widespread outside of urban centers.

Professionally managed

Professionally managed water systems are typically constructed, operated, maintained, and managed by trained staff who are paid to perform these duties. In the professionally managed approach the role of water users in planning and implementing the water project is emphasized less than in the previous management approaches. The costs of ongoing system operation and repairs are typically covered or offset by user fees (tariffs) or local taxes. Professionally managed supplies generally operate with legal recognition, with the associated accountability mechanisms in place. Professional management also often represents a broad spectrum in terms of the levels of sophistication and performance. This management type is most commonly applied to centralized piped schemes in urban areas or small towns (System 2 Centralized surface water treatment, D.5 Centralized distribution systems), where economies of scale enable financing of the infrastructure.

Complementary or hybrid approaches

The management typologies described here are not mutually exclusive; in practice a mixed service delivery model that combines elements from various management typologies may be better suited to the local context. Furthermore, each of the three typologies can be disaggregated into sub-models (World Bank, 2017). For example, it is estimated that the costs to governments in Zambia and Zimbabwe could be reduced by up to 40% if community water supply services in rural areas were complemented with a supported form of self-supply, i.e. self-financed family

wells (Sutton & Harvey, 2017). A comparative study of rural water supply projects globally examined the conditions leading to sustained functionality of water systems. For all management models, good financial practices and user participation in system planning were important for achieving sustained services. Typically, professionalized water systems required strong external support in the post-construction period. Self-supply systems operated well under conditions of abundant freshwater availability, whereas community managed systems operated best in areas where alternative freshwater sources were less available (Marks et al., 2018).

Due to the inherent challenges with traditional community management models (e.g. operating based on voluntary principles, often in the absence of sup-

porting legal recognition, training and accountability structures), there is increasing recognition of the need to couple community management with robust external support programmes (X.11 External support programmes), and eventually shift towards greater professionalization of community management. In this context, professionalization refers to water supplies that function within defined legal and accountability frameworks, and are operated, maintained, and/or managed by trained individuals (Lockwood, 2021). This approach involves providing the necessary policy, legal and regulatory frameworks, and support services, to ensure the supply can operate to agreed standards with greater transparency, accountability and efficiency (IRC, 2015).

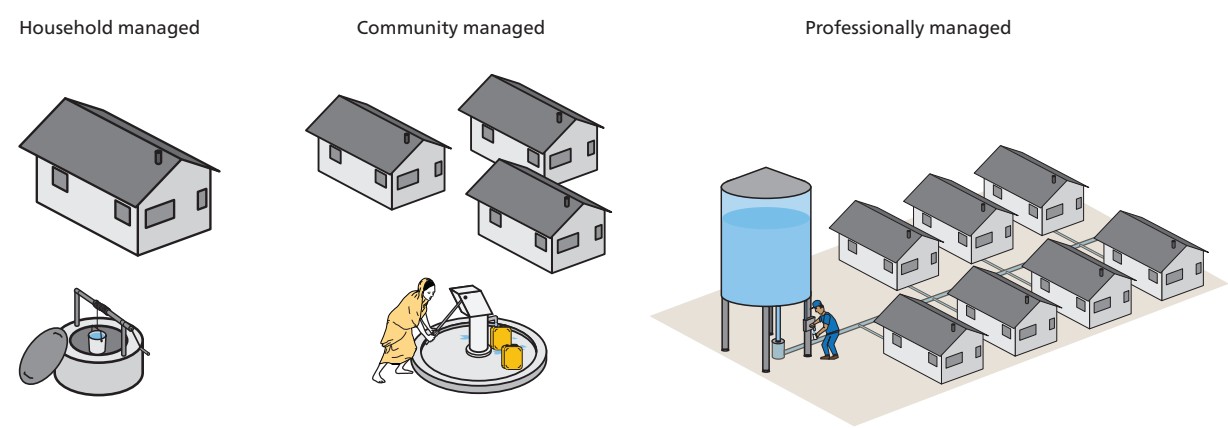


Fig. 1
Examples of infrastructure arrangements for three management models: a household managed family well, a community managed borehole equipped with a handpump, and a professionally managed piped network.

X.2 Gender and inclusion

Gender refers to the roles men and women are expected to play in society and the relationships of power between them. Inclusion refers to making specific efforts to ensure meaningful participation of all groups in a society, including disadvantaged groups.

Around the world, women and girls bear the primary responsibility for water collection and management at the household level. When water sources are distant or difficult to access, this burden limits their social, educational, political, and economic participation. In addition, women are poorly represented in water decision-making, and water collection may expose them to physical injury and violence. However, these disadvantages vary considerably based on socioeconomic class and the cultural and geographic context. Not all women are disadvantaged in the water sector, and other social groups may also face participation barriers.

A historical perspective

In the 1980s, international water programmes and governments began to stress the importance of including women in water supply planning and management. These initiatives were based on the idea that water programmes could unlock opportunities for women by reducing the time spent collecting water and providing new skills and roles in the community. Research indicates that water projects that address gender at each phase of planning and implementation are more equitable as well as more sustainable and effective (Gross et al., 2000; Cairncross, 1992). When men and women (both rich and poor) are active participants and decision-makers, water services are more likely to be used.

However, all too often, gender and inclusion is not meaningfully addressed in the context of water supply planning, and water services are therefore unlikely to meet all needs. Disadvantaged groups, including women, continue to face considerable obstacles participating in and benefitting from water projects. The Sustainable Development Goals (SDGs) prioritize reducing inequalities through a “leave no one behind” approach, and the SDG related to water and sanitation specifically focuses on meeting the needs of women, girls and vulnerable groups (UNDP, 2018). These imperatives underpin practical guidance on equitable water supply planning and implementation (WSP, 2010; WHO, 2019b).

Inclusion: Moving beyond women

Inclusion means more than simply including women. Other social groups that have historically been excluded

from participating in water programmes include children; people with living with disabilities or chronic illnesses including HIV/AIDS; the elderly; members of specific castes, religions, and ethnic groups; indigenous groups; and those living in remote or peripheral areas. Without an inclusive planning approach, water projects can reinforce existing inequalities. An inclusive approach should ensure that women and other disadvantaged groups have the opportunity to participate and benefit from water projects. Care must be taken to understand the different social groups within a community and to identify which groups are disadvantaged or have specific needs in relation to water access and decision-making.

Although women typically have less power and access to services, resources, and opportunities than men, gender roles and relationships change over time and are culturally determined. Gender roles and relations are also partly shaped by water access such that they can be renegotiated as water services improve. For example, with the installation of new water points closer to their homes, women might have more time for new income-generating activities that could increase their decision-making power in the household. However, these connections should not be taken for granted: women may enjoy the social time spent collecting water or be unable to control the money they earn (Van Houweling, 2016). While women’s empowerment is an oft-claimed goal of water projects, there may be other constraints that prevent women from realizing the benefits of improved water access, such as socio-cultural norms or the lack of economic opportunities. Gender also intersects with and reinforces power differences based on class, caste, ethnicity, race, education, age, and religion to shape water rights, access, and use. Therefore, not all women have the same rights and interests and should not be approached as a homogenous group.

Gender and social analysis

A gender and social analysis is used to help design more effective and equitable water services. This analysis should be used to understand the relative disparities or disadvantages within families and communities and the barriers different groups face in fully participating and benefiting from improved water services. A gender and social analysis is important because each social group often has different motivations, perceptions, priorities, and capacities related to water. For example, women living with disabilities may differ from other community members in their preferences for the water point’s location, the type of technology, and the level of service provided.

At its most basic level, a gender and social analysis seeks to understand who has rights, control, and access to water resources and services. This analysis often starts with an understanding of the differences among and between men and women (who does what work, who makes which decisions, who uses water for what purpose, who controls which resources, who is responsible for different family obligations, etc.), but it should also analyse the implications of water projects for all relevant social groups.

There are many participatory techniques for systematically collecting this information, which can be explored in the references provided.

Toward equity mainstreaming

Equity mainstreaming is the process of assessing and addressing the implications of a water service programme for different social groups during the planning, implementation, monitoring, and evaluation phases.

Some of the key activities for equity mainstreaming (including gender and social considerations) are outlined in Table 3. The implementation of these activities demands certain attitudes and principles, such as listening, being flexible, respecting local knowledge, taking time, and adopting inclusive communication styles and formats.

A gender transformative approach should seek to address underlying power dynamics that give rise to social inequalities and should work towards women's economic advancement through water, especially through their involvement in small-scale enterprises. Such an approach would also look beyond the community level and might include institutional gender training, advocacy for high-level commitments to gender equality, gender-responsive budgeting, and the explicit recognition of women and other disadvantaged groups as users and managers in water laws and policies.

Planning	Implementation	Management	Monitoring and Evaluation
Conduct a gender and social analysis to understand gender roles related to water and the relative disadvantages different social groups face in terms of access, control and use of water resources, taking a 'do no harm' approach	Offer additional trainings in areas such as micro-credit, small enterprise development, and leadership to help women capitalize on the benefits of improved water access	Support the inclusion of under-represented groups in leadership positions on water management committees	Collect data disaggregated by gender and socioeconomic class about water access, rights, use, and impacts
Examine and address the barriers women and other disadvantaged groups might face in participating in planning and management	Partner with existing women's groups and NGOs that have expertise on gender issues, empowerment and social inclusion	Offer women and other marginalized groups trainings and roles in areas providing new skills and opportunities	Monitor potential social exclusions and address any barriers social groups face in benefitting from the improved services and having specific differentiated needs met
Design water services inclusively and ensure that women and other disadvantaged groups are meaningfully included in decision-making	Work with power holders to change cultural norms that inhibit the participation of women and other disadvantaged groups	Ensure that new opportunities to participate in the management of the water supply do not contribute to an overburden of unpaid and often informal labor (i.e., 'do not harm' approach)	Include women and other under-represented groups in deciding what goals and outcomes will be evaluated and how they will be evaluated

Activities for gender and social mainstreaming

Table 3

X.3 Life-cycle and environmental impact assessment

Life-cycle assessment (LCA), also called life-cycle or cradle-to-grave analysis, is a tool that integrates global environmental impacts into the choice and planning of drinking-water system designs.

LCA is an International Organization for Standardization (ISO) 14040 normalized method to evaluate the environmental performance of a product or service through all the life-cycle phases. It includes resource consumption, production, utilization, and disposal aspects.

Four steps are necessary to conduct a LCA:

- Goal and scope definition
- Life-cycle inventory (LCI)
- Life-cycle impact assessment (LCIA)
- Life-cycle interpretation

Even though the steps are successive, an iterative process is required (Fig. 2).

Goal and scope definition

A first step of the LCA is to identify the purpose and the target audience. This also determines the type of LCA performed (i.e. comparative or non-comparative). Setting this scope defines what will be analysed and how, and it defines the system boundaries (Fig. 3). When considering LCA for water supplies, three main system boundaries could be highlighted:

- Water supply system (intake to user)
- Water production (from source to treatment)
- Technology (e.g. treatment)

To fairly compare between different systems, the functional unit needs to be clearly defined. In drinking-water LCAs, it is usually the volume of water delivered with a specified quality (e.g. 1 m³ of drinking-water quality water delivered as specified by the country guidelines).

Life-cycle inventory

LCI lists all the inputs required and all the outputs generated by the construction and operation of the system components:

- Construction materials (e.g. concrete, steel)
- Energy consumption (e.g. heat, electricity)
- Chemical consumption (e.g. coagulants, activated carbon, chlorine)
- Output water/waste streams (e.g. backwash water, treatment sludge)
- Emissions to air (e.g. chlorine gas, dust)

All inputs and outputs are expressed based on the functional unit.

Life-cycle impact assessment

The purpose of the LCIA is to better understand the environmental significance of the LCI results. LCIA transforms inflows and outflows into defined environmental impact categories:

- Climate change: global warming potential
- Human health: ionizing radiation, respiratory effects
- Natural environment: ozone layer depletion, terrestrial acidification/nitrification
- Natural resources: mineral extraction, non-renewable energy consumption

For each impact category, the impact value is expressed by its equivalent weight of a reference substance: e.g. global warming potential is expressed in terms of grams of CO₂ equivalent per functional unit (e.g. m³ of water).

To help convert inputs and outputs to quantified environmental impacts, inventory databases such as Ecoinvent, U.S. Life Cycle Inventory Database, European Reference Life Cycle Data system are available. Such databases can be used with LCA software, such as OpenLCA, SimaPro, or GaBi.

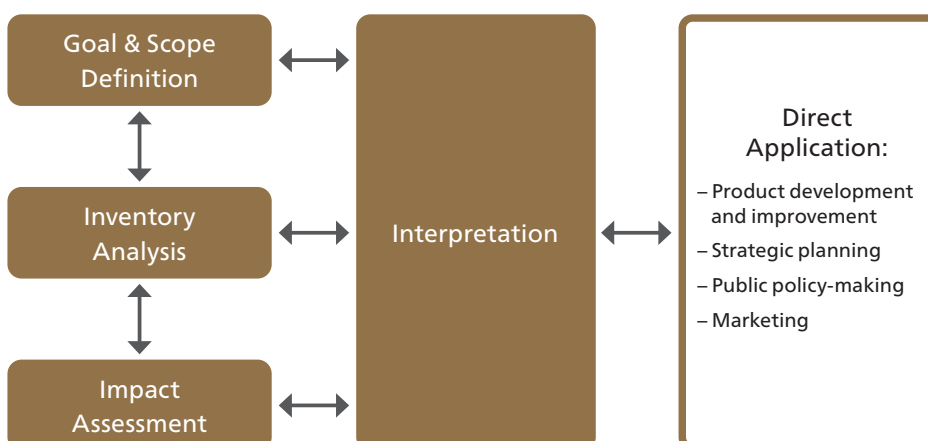


Fig. 2
General LCA methodological framework (ISO 14040:2006; © ISO, 2006)

Since the inventory databases were developed primarily in Europe and are location specific, they usually have to be adapted when applied in other locations, especially when considering low- and middle-income settings. Data adaptation is a critical stage that can influence the robustness of drinking-water LCAs.

Fig. 4 shows an example of LCIA results from a study on alternative drinking-water supplies comparing the environmental impact of local groundwater extraction (System 6 High-quality groundwater), distant surface water treatment and transfer (System 2 Centralized surface water treatment), local seawater reverse osmosis desalination (SWRO) (System 9 Desalination of brackish and salt water, T.5.2 Reverse osmosis), and local seawater multi-effect distillation (MED) (System 9 Desalination of brackish and salt water, T.5.1 Membrane distillation) (Vince et al., 2008). The y-axis shows the results of the various alternatives in percent as compared to the highest value. In this particular case, local MED desalination had the highest values for the eight environmental impacts that were considered and is

therefore the worst alternative. In contrast, local groundwater treatment is the best option, scoring less for all the environmental impacts that were considered.

Life-cycle interpretation

Interpretation is the phase where the findings from the LCI and the LCIA are analysed together. The results should be consistent and in line with the defined goal and scope. If this is not the case, the goal and scope have to be re-defined and the analysis re-run. At the end, the results should reach a conclusion, explain limitations, and provide recommendations in support of more informed decisions.

Limitations

LCA focuses on environmental issues, and as such, does not address economic or social aspects. For ensuring a general LCA, other tools such as risk assessment, life-cycle costing, and social analysis should also be considered.

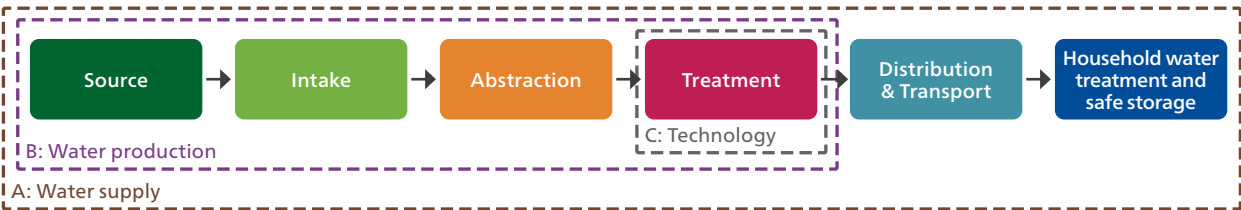


Fig. 3
Drinking-water LCA system boundaries

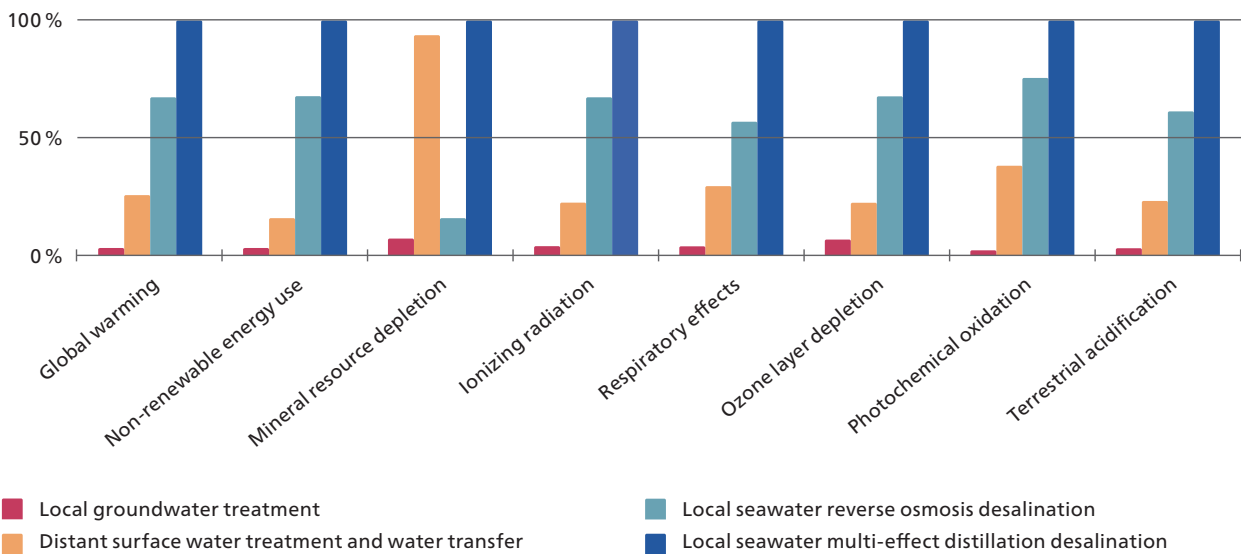


Fig. 4
Example of LCIA results on drinking-water alternatives (adapted from Desalination, 220(1–3), Vince et al., LCA tool for the environmental evaluation of potable water production, p. 37–56, Copyright (2008), with permission from Elsevier)

X.4 Risk assessment and risk management

Risk assessment and risk management is a preventive approach for identifying, prioritizing, and mitigating risks within the water supply system. Such approaches should cover the entire water supply from catchment/source to consumer. In the WHO *Guidelines for drinking-water quality* they are referred to as water safety plans (WSPs; WHO, 2022a).

Pathogens in drinking-water are a main cause of acute gastrointestinal illnesses, especially among children under age five (WHO, 2019c). Long-term exposure to elevated levels of chemical contaminants in drinking-water can cause adverse chronic health effects. Water for drinking should not exceed accepted standards for these contaminants, and water used for food preparation, personal hygiene, recreational use, livestock, and irrigation should not pose significant risks to public health. This chapter summarizes the main elements of risk assessment and risk management approaches for water supplies.

A key tenet of any risk assessment and management approach is a shift away from focusing solely on end-of-pipe water quality testing, which is inadequate for planning timely and effective responses. Instead, risk-based approaches focus on preventive measures through applying and routinely monitoring appropriate barriers (or control measures) to prevent hazardous events from happening in the first place. Several risk-based frameworks have been developed for use in the water sector. Water safety planning is considered the most effective approach for consistently ensuring the safety of a drinking-water supply (WHO, 2022a). Water safety planning integrates risk assessment and prioritization (typically using risk assessment matrices), alongside monitoring, management, and communication, to achieve stepwise continuous improvement (see X.5 Water safety planning). Sanitary inspection is a simple risk assessment approach to provide a rapid on-site assessment to determine if priority risk factors are present that can lead to contamination of the water supply. Sanitary inspections can support water safety planning, and in some contexts, may be a simplified alternative to water safety plans (WHO, 2024a), typically performed using basic sanitary inspection forms (see X.6 Sanitary inspection). Among the most intensive methods for assessing microbial health risks of drinking-water supplies is quantitative microbial risk assessment (QMRA), which integrates data on pathogen exposure, infectivity rates, and intervention effectiveness (see X.7 Quantitative microbial risk assessment). Both sanitary inspection and QMRA are tools that can support water safety planning and serve the risk management process.

Assessing contaminants of concern

Risk assessment involves understanding the potential threats (or hazards) to the water supply system at each step, i.e. source/catchment, treatment (if any), distribution/storage, and household level, and prioritizing the risks that are deemed to be most significant. Risk assessment requires training and experience, with inputs from water suppliers and public health, catchment, and consumer representatives, among others.

Classes of hazards typically relate to microbial, chemical, radiological, acceptability, and quantity-related hazards. Hazards can be of human (anthropogenic) or natural origins and pose various risk levels, which should be assessed and prioritized to determine specific and appropriate management actions.

Pathogens are disease-causing microorganisms, such as viruses, bacteria, protozoa (parasites), and helminths. Faecal contamination is considered to be the most significant risk to public health associated with drinking-water quality (WHO, 2022a). Even a few pathogens in a glass of water can cause an infection, and an infected person or animal can release millions of pathogens into the environment through feces. Surface water is more likely to contain pathogens, especially near human activities such as wastewater discharge, open defecation, or manure application (see System 8 Freshwater sources subjected to anthropogenic contamination. Contamination during storage and distribution can occur in centralized supplies (open reservoirs, intermittent piped supply, e.g. System 2 Centralized surface water treatment) or on household premises (open vessels, hands, animals, dirty cups; see H. Household water treatment and safe storage). An insufficient or improperly functioning treatment step may not fully remove or even introduce contamination, while inadequate maintenance and repair activities or backflow in the distribution system may introduce contamination into the system. Protected surface waters will contain less pathogens, although wild animals may still contaminate the water. Groundwater sources from aquifers that are unprotected, shallow or under the direct influence of surface water are vulnerable to contamination. Protected groundwater from deeper aquifers is likely to be pathogen free, although contamination could be introduced via extraction infrastructure. Protective measures include *inter alia*, safe local management of faecal waste, a protective (clay) layer above the aquifer, or a properly constructed protected well.

Chemical and radiological contaminants in water sources generally do not cause acute (i.e. short-term) health effects, but long-term exposure may detrimentally impact health (e.g. developmental effects, cancer, and a range of chronic diseases). Naturally occurring

chemical contaminants of concern include arsenic and fluoride, which can be present in groundwater aquifers. High-risk areas are often known and can be identified in online databases. However, changes in groundwater abstraction or climate can mobilize these contaminants.

Anthropogenic contaminants can affect both surface water and groundwater, and they originate from various activities like agriculture (nitrate, pesticides), industry and mining (heavy metals, chemicals), and households (faecal pollution). It is impossible and costly to analyse water for all possible contaminants. As such, a risk-based approach should be undertaken, whereby the risk posed by anthropogenic contaminants may be estimated from the various activities in the catchment, distance to the water source, transportation, attenuation, and other factors.

Risk management approaches

Following risk assessment is risk management, which includes identifying, implementing, and monitoring appropriate barriers to provide a safe and reliable water supply. This includes treatment designed to address known risks, as well as a multi-barrier approach that considers the source, treatment (if present), distribution, and user levels. QMRA can be used to assess if barriers against specific pathogens of concern are sufficient, though the required information, knowledge, and expertise for this level of risk assessment may not be available, e.g. for small decentralized or household treatment systems. In such cases, known hazards can form the basis for technology selection. In regions known to have high arsenic or fluoride concentrations, risk management generally includes avoiding contaminated wells or implementing specialized treatment at the household or community level.

Supporting activities can enable the consumer or small-scale operator to manage drinking-water risks.

These programmes can be implemented by local or national governments, private companies, or non-profit organizations. Supporting programmes should include several activities:

- Awareness raising
- Knowledge building (education)
- Stakeholder engagement
- Resource and training availability
- Research to identify adequate measures for addressing risks
- Programmes to protect water from contamination

Examples of awareness raising include flyers, health-care visits, community walks, songs or theatre, community meetings, radio-, TV- or social media messages, and internet games. Hygiene may be taught at school and transferred to parents. Specific training programmes may be implemented, especially for small-scale treatment operators.

Reliance on water treatment alone as an end-of-pipe solution is inefficient and often ineffective due to technical and implementation challenges. A thorough risk assessment and risk management approach will better safeguard the long-term safety of drinking-water supplies, especially by enabling timely and effective responsiveness to potential hazards. An effective risk framework evolves over time, recognizes risks may arise from a range of hazards (not only contamination-related), and is a continuous cycle of improvement that responds to changes within the system, including landuse, climatic, and population changes. It should be reviewed routinely and revised as needed to ensure it is up-to-date, including following incidents. Monitoring the achieved progress will provide verification of the effectiveness of the risk management approach and incentives for further improvement of the water system.

X.5 Water safety planning

A water safety plan (WSP) is a comprehensive, proactive risk assessment and risk management approach to most effectively ensure drinking-water safety. It is an ongoing and dynamic process that enables the preventive management and monitoring of risks throughout the entire water supply, from catchment to consumer.

The *Guidelines for drinking-water quality* recommend that all water suppliers apply the principles of water safety planning as the most effective means of ensuring the safety of drinking-water supplies (WHO, 2022a). Water safety planning is a preventative approach. It moves away from relying only on “end of pipe” testing to confirm drinking-water safety, which is a reactive approach where users may have already been exposed to unsafe water by the time it is detected through monitoring. WSPs help to enable source protection, effective treatment, sanitary distribution and storage, and safe practices at the user level. Water safety planning has been successfully applied at different scales and socioeconomic settings globally (WHO, 2017d). Key terms used in WSPs are defined in Fig. 5.

WSP stages

Water safety planning is a continuous and iterative process for making progressive improvements in safe drinking-water management (i.e. starting simple, with stepwise improvement as capacity and resources allow). The approach is typically led by the water supplier, where each step of the water supply chain is assessed to identify and manage priority risks to the supply of safe drinking-water. The stages of WSP include the following activities.

- **Preparation:** engaging key stakeholders (including decision-makers) and securing their commitment; establishing a WSP team with the relevant experience to drive the development and implementation of the WSP.
- **System assessment:** describing the entire water supply system from catchment to consumer to identify threats (hazards/hazardous events); assessing and prioritizing the risks associated with the threats; developing and implementing a progressive improvement plan to address priority risks.
- **Monitoring:** routinely monitoring barriers (control measures) through operational monitoring to ensure that they are operating as intended, and applying timely corrective actions where needed; ongoing verification of the effectiveness of the WSP as a whole, through water quality monitoring (compliance monitoring; see X.9 Water quality monitoring), WSP auditing, and monitoring consumer satisfaction.
- **Management and communication:** developing standard operating procedures for day-to-day activities, as well as during emergency situations (emergency response plans), and developing programmes that support and improve safe drinking-water management.
- **Feedback and improvement:** conducting regular and as-needed reviews, revising the WSP as required to ensure the WSP is up to date and reflects operational experiences.

WHO provides detailed guidance on water safety planning for larger systems (e.g. System 2: Centralized surface water treatment; WHO, 2023) as well as for small water supplies (e.g. System 3: Decentralized surface water treatment; WHO, 2012b; 2022b). The WSP steps are summarized in Fig. 6.

WSP principles can strengthen the resilience of water supplies for emergency and unforeseen events, including those arising from conflict, pandemics, and the affects from climate variability and change (see X.12 Strengthening resilience to climate change).

Water safety planning can be harmonized with other existing risk management approaches (e.g. Hazard Analysis & Critical Control Point) and the International Organization for Standardization (ISO) risk management guidelines.

Benefits of water safety planning

Sustained and effective implementation of a WSP may bring considerable benefits, including:

- Improved water quality and a reduced prevalence of waterborne diseases
- Better system understanding, including of the risks relating to public health
- Improved operation and management practices, and associated cost efficiencies
- More targeted resource allocation on the basis of risk
- Increased leveraging of financial support
- Improved stakeholder collaboration and knowledge-sharing
- Greater user confidence in the safety of the water supply

Sustaining effective WSP implementation

Practical application of WSPs globally has identified several practices that underpin successful water safety planning. This includes integration with ongoing operations, management, and monitoring activities, coupled with regular review and updating as needed in response to change and operational experiences. For more information, see Fig. II.1 in WHO (2023).

National top-down WSP directives (e.g. policy, regulations) play an important role in enabling WSP uptake.

Hazard A contaminant or condition that may adversely affect the supply of safe drinking-water.	Hazardous event An event that results in a hazard being introduced to, or inadequately removed from, the water supply.
Control measure An activity or process to prevent, eliminate or reduce the risk of a hazardous event to an acceptable level.	Control measure validation Obtaining evidence that the control measure can effectively control the corresponding hazardous event.
Risk The product of the likelihood of occurrence of a hazardous event and its severity (or consequences).	Improvement plan An action plan for improving the level of control for a hazardous event, thereby reducing the level of risk.
Operational monitoring A plan to monitor control measures to ensure that they work as intended, and that proper and timely corrective action is taken when predefined limits are not met.	Verification The process of obtaining evidence that the WSP, as a whole, is working effectively to deliver safe drinking-water.
Compliance monitoring The process of determining compliance with drinking-water quality regulations and standards.	WSP audit An independent and systematic check to confirm that the WSP is complete, adequately implemented and effective.

Fig. 5
Glossary of select water safety planning terms (WHO, 2023)

Guidance on regulatory aspects of water safety planning in small supplies can be found in *Guidelines for drinking-water quality: small water supplies* (WHO, 2024a). However, WSP directives alone are insufficient unless complemented by genuine water supplier support. To achieve this, targeted advocacy plays an important role, communicating the benefits and impacts of WSP uptake to key stake-holders, from operational level to management level.

Surveillance programmes (including WSP auditing) underscore WSP sustainability by enabling the enforcement of regulatory requirements and providing incentive and ongoing support to suppliers. Where relevant, a pragmatic approach to auditing is encouraged, which demonstrates the practical value of WSPs.

Effective water safety planning requires sustainable financing. For national WSP programmes, financing is needed to support WSP capacity development and to oversee the ongoing implementation by water suppliers. At the water supply level, WSP implementation requires ongoing funding, particularly where the WSP identifies issues to be addressed. Where shortfalls exist for water suppliers, funding mechanisms should be established e.g. using improvement plans to inform annual budget allocations (WHO, 2024a).

In rural settings, WSPs can integrate other WASH initiatives that may already be in place, including household water treatment and safe storage, hygiene promotion, and community-led total sanitation. There is a need to ensure that WSP activities are streamlined and harmonized with related programmes from governments and development partners to avoid mixed messaging or resource duplication.

Importance of customization and training

The WSP approach is flexible and should be adapted to the local circumstances, commensurate with the complexity of the water supply and the available resources and capacity. Basic WSP templates can be a useful tool to support early-stage WSP development (see WHO, 2022b), and can be customized to suit the local context. In resource-constraint settings, sanitary inspection may also be considered as a simplified alternative to water safety plans (e.g. household managed supplies; WHO, 2024a).

Water suppliers require training and ongoing technical assistance to effectively implement WSPs. This includes training on the process and supporting tools, and also guidance on addressing the priority risks identified through the WSP process. Water suppliers can also play a supporting role for each other, e.g. through peer-to-peer support mechanisms and knowledge exchange visits. Where possible, water supplier

training on WSPs should be integrated into broader operator training and certification programmes (WHO, 2024a).

Enablers and barriers: the case of Uganda

The following factors were shown to enable or impede WSP development and implementation in Uganda (Kanyesigye et al., 2019), which have relevance globally.

⊕ Enablers

- Strong managerial commitment
- Sense of responsibility toward public health
- Good customer relation practices
- Availability of financial resources
- Reliable laboratories

⊖ Barriers

- Water suppliers viewing a WSP as creating additional and unnecessary work
- Inadequate training
- High staff turnover
- Lack of resources (e.g. financial, laboratory capacity)
- Inability to design and carry out WSP auditing programmes

WSP Stages	WSP modules for larger supplies (WHO, 2023)	WSP tasks for small communities (WHO, 2022b)
Preparation	Module 1Assemble the WSP team	Task 1Engage the community and assemble a WSP team
System assessment	Module 2Describing the system Module 3Identifying hazards and hazardous events Module 4Validating existing control measures and assessing risks Module 5Planning for improvement	Task 2Describe the water supply Task 3Identify and assess hazards, hazardous events, existing control measures and risks Task 4Develop and implement an incremental improvement plan
Monitoring	Module 6Monitoring control measures Module 7Verifying the effectiveness of water safety planning	Task 5Monitor control measures and verify the effectiveness of the WSP
Management and communication	Module 8Strengthening management procedures Module 9Strengthening WSP supporting programmes	Task 6Carry out operations and maintenance and plan for emergencies
WSP review and improvement	Module 10Reviewing and updating the WSP	Task 7Review and improve all aspects of WSP implementation

Fig. 6
Overview of WSP steps as described in WHO guidance manuals

X.6 Sanitary inspection

Sanitary inspection (SI) is a simple and powerful risk assessment approach to help identify and manage priority risk factors that may lead to contamination of a water supply.

SI is an on-site assessment that typically makes use of standardized forms (SI forms) that consist of a checklist of equally weighted yes/no questions that indicate the presence or absence of observable risk factors (Fig. 7). The number of “yes” responses (i.e. risk factors present) is totalled to provide a sanitary risk score that can be used to prioritize action.

WHO (2024b) provides 13 SI packages for different water supply technologies and scenarios. Each package consists of the following elements.

SI form: provides a checklist of yes/no questions, supported by illustrations depicting the water supply technology or scenario in an insanitary condition, to help identify common risk factors and prompt corrective action.

Technical fact sheet: gives basic technical information (with supporting illustrations of the technology or scenario in a sanitary condition) to aid completion of the SI form.

Management advice sheet: provides general guidance on developing an operations and maintenance schedule to support the safe management of the water supply, alongside basic corrective actions to consider for each risk factor included in the SI form.

In line with water safety planning principles (X.5 Water safety planning), completion of the SI form should be complemented by planning and action for improvement, ongoing maintenance, and monitoring in accordance with the guidance in the corresponding management advice sheet.

SI should be completed by trained individuals with an understanding of public health aspects of drinking-water supply. It is conducted through an on-site visit to identify common risk factors that may lead to contamination of the water supply, related to the physical infrastructure supply, its operation, and external environmental factors.

SIs provide a low-cost, easy-to-use tool that is particularly suited to resource limited settings, including small water supplies. SI can be applied to point sources (such as Systems 1, 4, 5, 6, 7) as well as piped water supply (such as Systems 2, 3, 8, 9).

Applications of sanitary inspection

SI can be applied to support the following activities (WHO, 2024a).

- **Routine risk management by water suppliers:** where a WSP is in place, SI can support the identification of risk factors and corrective actions, as well as on-

going maintenance and monitoring (see X.5 Water safety planning). Where there is no WSP in place, SI can be used as an interim risk assessment and management tool while WSP capacity is developed in parallel. Simplified SI can also be applied as an alternative to WSPs in the case of household managed supplies, with appropriate supports in place.

- **Assessment of risk management practice by surveillance authorities:** SI can support surveillance activities to help determine that priority risks are being effectively managed and to inform corrective action by water suppliers. The aggregated outcomes from SIs can also inform broader policy and programme development.

Sanitary inspections and water quality testing

Results from SI and water quality testing (see X.9 Water quality monitoring) can be jointly analysed to identify the most important causes of water supply contamination and associated preventive and remedial actions. Ideally, the sanitary risk score should be combined with data from water quality testing (e.g. see Figure 5.2 in WHO [2024a]) as part of an overall risk assessment of the water supply. However, due to the dynamic nature of both observable risk factors and water quality (particularly microbial water quality as measured by faecal indicator bacteria), SI scores and water quality testing results often do not exhibit a consistent positive linear relationship i.e. one metric cannot be used to reliably predict or infer the other.

Where there is insufficient capacity or resources to carry out water quality testing, SI can still provide valuable information to support safe drinking-water management.

Importance of customization and training

The SI packages can be used directly in the format provided by WHO (2024b). However, certain aspects of the packages may not be relevant in all contexts given that water supplies vary widely, or additional risk factors may be important in some settings. If needed, authorities can adapt the material to the local context as capacity and resources permit. Context appropriate and relevant SI forms may support acceptance and uptake of SI as a risk assessment tool. For further guidance on adapting SI packages, see Annex 4 of *Guidelines for drinking-water quality: small water supplies* (WHO, 2024a).²³

Inspector ability may also affect SI outcomes, in particular where perception of risk is required. Effective training is therefore critical to improve the accuracy and consistency in assessments between individuals conducting a SI.

Sanitary inspection

⊕ Advantages

- Quick and easy to use
- Supports risk management, including where a full WSP is not feasible
- Supports engagement with water supply owners/operators (i.e. via communicating the outcomes of the SI)
- Can inform evidenced-based programming via aggregated results from water supplies
- Complements water quality monitoring, encouraging necessary corrective actions
- Applicable in a broad range of settings

⊖ Disadvantages

- Less comprehensive than WSPs
- Does not capture all risk factors within a water supply (e.g. chemical risks)
- Assumes each risk factor carries equal weighting (i.e. equal potential to cause contamination)
- A “one-off” SI does not capture the variability in conditions and practices that occur over time
- Accurate interpretation of risks can be hampered by untrained inspectors



Fig. 7
Extract of a completed SI form and supporting illustrations for rainwater collection and storage (adapted from WHO, 2024b)

SANITARY INSPECTION FORM		DRINKING-WATER			
Sanitary inspection questions		NA	No	Yes	If Yes, what corrective action is needed?
1	Are there any visible contaminants on the roof or in the guttering channels? Contaminants on the roof or in the guttering channels (e.g. from animal faeces, corroded or damaged roof or gutter materials, leaves, moss) could contaminate the water. This could also cause blockages and an overflow, which could result in water loss.	☐	☐	☒	Clean out the gutters and communicate the importance of regular cleaning.
2	Do the roof or guttering channels have an inadequate slope for drainage? Stagnant water could contaminate the water supply if the roof or guttering channels do not have a downward slope for water to fully drain into the storage tank. Note – ponding of water on the roof or in the guttering channels may indicate an inadequate drainage slope.	☐	☒	☐	
3	Is there any vegetation or structures above the roof? Contaminants (e.g. from animal faeces) could enter the water supply if there is overhanging vegetation, balconies or wires above the roof. Fallen leaves could also block gutters and cause an overflow, which could result in water loss.	☐	☐	☒	Cut the tree branches that hang over the roof.
4	Is the filter box absent, damaged or blocked? Contaminants could enter the water supply if the filter box is absent. This could also happen if it is damaged (e.g. holes or gaps in the filter screen) or blocked (e.g. from sediment, leaves). A clogged filter box could also cause an overflow, which could result in water loss.	☐	☒	☐	
5	Is the first flush system absent, damaged or blocked? Contaminants from the first flush of rainwater could enter the water supply if the first flush system is absent. This could also happen if it is damaged (e.g. not flushing completely) or blocked. A blocked first flush system could also cause an overflow, which could result in water loss.	☐	☒	☐	

23 To support adaptation, editable versions of the 13 WHO sanitary inspection packages are available from <https://www.who.int/teams/environment-climate-change-and-health/water-sanitation-and-health/water-safety-and-quality/water-safety-planning/sanitary-inspection-packages>

X.7 Quantitative microbial risk assessment

Quantitative microbial risk assessment (QMRA) is a method for assessing human health risks from microbial pathogens in water supply systems by incorporating data on the concentration, fate, and transport of pathogens in the environment; human-environment interactions; pathogen infectivity; and intervention efficacy.

Similar to other risk assessment approaches (e.g. sanitary inspection and risk matrices as applied in water safety planning), QMRA is used to estimate health risks and facilitate the prioritization of control measures to improve the safety of water supply systems.

Overview

QMRA provides a quantitative, evidence-based, and reproducible framework to relate water safety management to population-level risks of infection, illness, and sequelae (i.e. conditions caused by a previous disease or injury). The framework provides insight into the links between microbial contamination of water supplies and adverse health outcomes. QMRA consists of four interrelated steps, as detailed by the WHO harmonized framework (Fig. 8; WHO, 2016b):

- Problem formulation
- Exposure assessment
- Health effects assessment
- Risk characterization

The QMRA framework is intended to be iterative, with information gained during the final step (risk characterization) informing efforts to better refine data gained in the previous steps.

Application

Outputs from QMRA can be used to support local or national regulations and guidelines. Examples include: 1) quantifying risks from pathogen exposures through water supplies, 2) identifying appropriate, effective interventions and their impacts on risks, and 3) developing guidelines for the minimum required efficacy of interventions.

No intervention can eliminate all risks of enteric pathogens from water supplies; rather, the goal of interventions is to reduce risks to a tolerable level. Tolerable is defined as a level of health risk that is acceptable by society for a specific exposure or disease (WHO, 2016b). QMRA aids in identifying risks and reducing them below the threshold.

Quantitative estimates used within QMRA come from multiple sources, including original (primary) data, literature reviews, and expert opinions. The estimates can be described as single, point values (deterministic) or as distributions describing a range of potential values (stochastic). The distributions are useful

because they provide insight into variability and/or uncertainty, which can be translated into recommendations for risk-based outcomes. Variability refers to natural fluctuations in values over time and space, and uncertainty refers to the confidence in estimated values. Increasingly, the scientific community is recognizing the need for stochastic QMRA models that account for uncertainty and variability (Schoen et al., 2017; WHO, 2016b).

QMRA can provide valuable quantitative inputs in to the water safety planning process, including for the system assessment (e.g. identifying which microbial hazards are driving consumer risks, or which sources of hazards are the most important), monitoring (e.g. identifying which parameters will provide a direct indication of microbial safety, setting appropriate operational targets and critical limits to ensure safety), and management and communication stages (e.g. identifying what minimum response time is adequate for different incidents, or which corrective actions are the most effective).

For more information, see *Quantitative microbial risk assessment: application for water safety management* (WHO, 2016b).

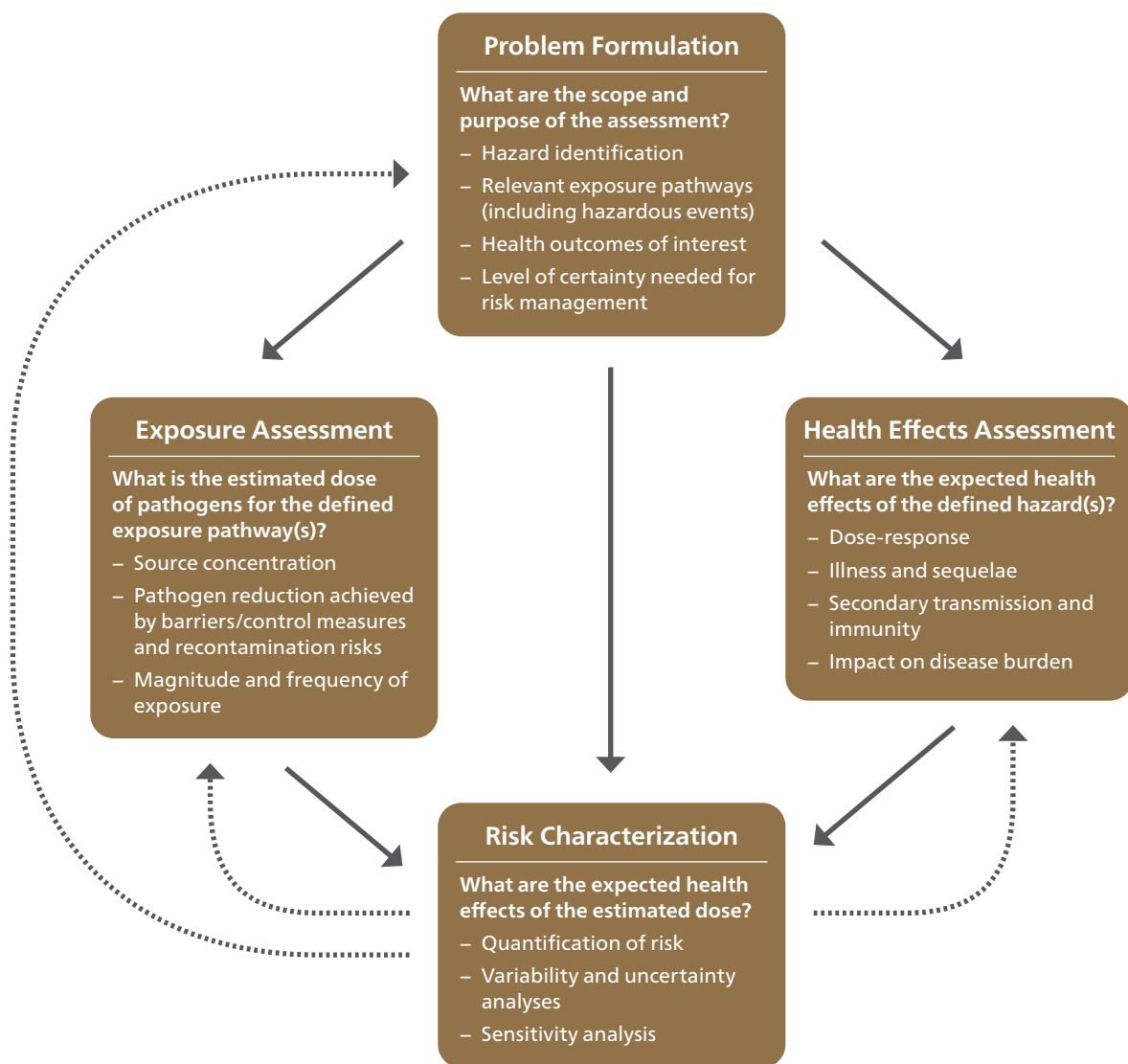


Fig. 8
The four interrelated steps of QMRA, adapted from WHO (2016b). Problem formulation informs the exposure assessment and health effects assessments, which in turn inform risk characterization. Risk characterization can be used to inform and update prior steps to improve or refine the assessment.

X.8 Drinking-water quality regulation

Regulations are a powerful tool to progressively improve and ensure the quality, safety and sustainability of drinking-water services to protect public health, as part of moving towards professionalized service delivery.

Regulations are rules or directives usually set by government agencies “to ensure that stakeholders fulfil their mandates, and that standards, obligations and performance are maintained (Jimenez et al., 2020)”.²⁴ The primary aim of drinking-water quality regulations is to safeguard public health through the supply of safe drinking-water.²⁵ Regulations help to ensure that water service providers are adequately supported, and held to account where necessary, towards improved public health outcomes relating to drinking-water safety. Regulations should provide clear direction on how the delivery of safe drinking-water can be achieved, and by what means it will be measured. In the absence of regulation, accountability and liability may be compromised, leading to increased risks to public health.

Regulations should adopt a “risk-based” approach to safe drinking-water management. This should include the requirement or promotion of context-appropriate risk management by water suppliers (e.g. X.5 Water safety planning or in certain contexts, X.6 Sanitary inspection), set appropriate limits for the identified priority parameters, and provide direction on targeted monitoring programmes that reflect the highest-priority risks (X.9 Water quality monitoring).

The development or revision of regulations involves the concerted effort of stakeholders concerned with drinking-water quality and public health (e.g. national public health authority, water supply authority, sub-national government agencies). External support and broad stakeholder engagement is important to ensure that regulations are robust, technically sound, and achievable in the given context (e.g. environment, agriculture, and resource management authorities; water suppliers, sector professional and industry groups; analytical laboratories; user representatives including disadvantaged and vulnerable groups). It is also important to ensure political and legislative support for regulations.

Content of regulations

Drinking-water quality regulations should include the following (after WHO 2018b and 2024a).

- **Risk management requirements by water suppliers:** proactive risk management by the water supplier is essential and thus, regulations should require or promote water safety plans to most effectively manage risks from catchment to consumer. Regulations should focus on the core elements of water safety planning.
- **Priority water quality parameters:** Water quality parameters should be prioritized to ensure that public health outcomes are maximized while ensuring the efficient use of resources (e.g. human, financial, technical). The *microbial* safety of the drinking-water should be the top priority (e.g. encompassing parameters such as *Escherichia coli*, turbidity, and where chlorination is practised, free chlorine residual and pH). Where specific *chemicals*²⁶ occur at concentrations of concern, these should be prioritized for inclusion. *Acceptability* parameters should be considered (e.g. taste, odour, appearance) where they may cause users to turn to other, potentially less safe sources.
- **Water quality parameter limits:** parameter limits should be set that are protective and realistic in the given context. In many settings, adopting the guideline values presented in the *Guidelines for drinking-water quality* (WHO, 2022a) will be appropriate for the prioritized parameters. Where these values cannot be applied (e.g. where the cost of achieving the guideline value outweighs the likely health benefit), alternative approaches can be considered by regulatory authorities. This may include setting a time-bound interim limit for specific parameters that is less stringent than the guideline value but still protective of public health, or specifying exemptions (which may or may not be time-bound) on the basis of insufficient resources to address a problem (or more broadly for the parameter due to lack of significance).
- **Monitoring frequencies and locations:** appropriate monitoring frequencies should be defined, considering factors such as the size of the general population and their vulnerability, the likelihood of the parameter being present at levels of concern, and the likelihood of the parameter concentration changing (including seasonal variations). Regulations should define appropriate monitoring locations considering the point in the water supply the parameter may be introduced or likelihood of change, known areas where water quality issues arise, location of vulnerable populations (e.g. health-care facilities, schools), the influence of user practices (e.g. household storage, treatment, and handling), among other factors.
- **Surveillance requirements:** risk-based surveillance requirements should be established within regulations to verify proactive risk management practice by water suppliers. This can be achieved by conducting water safety plan (WSP) auditing and/or sanitary inspection (see X.5 Water safety plan-

ning and X.6 Sanitary inspection. Surveillance also includes water quality testing, and reviewing the results of any compliance monitoring conducted by water suppliers (see X.9 Water quality monitoring).

Regulations may include specified technology targets for drinking-water treatment (where it is applied). These targets specify treatment devices or processes that are permitted for specific system types. This approach may be more common where resources and technical capacity for system specific assessments may not be feasible (e.g. in the case of small water supplies). Specified technology targets should consider the water characteristics and treatment objectives, as well as practical considerations such as costs, requirements for power, consumables (e.g. treatment chemicals, testing reagents), operation and maintenance, and supply chains (e.g. for consumables, spare parts; WHO, 2024a).

In addition, regulations may specify source protection measures, analytical requirements (including the permitted use of field test kits), household water treatment technology performance targets, material safety aspects (e.g. chemical additives for treatment, materials in contact with drinking-water) and requirements for operator training and skills. In some cases, these and other relevant requirements may be specified in separate regulations and associated frameworks, which may be referenced in the drinking-water quality regulations.

Clear regulatory requirements for data sharing and reporting are required to help ensure that information (e.g. from surveillance activities) is used to inform decision-making at the individual supply, as well as sector level, in the shorter to longer-term.

Ensuring context appropriate regulations

If due consideration is not given to the local resource realities, regulations will not achieve the desired public health outcomes and can result in inefficient use of limited resources. Regulations therefore should follow a stepwise approach to first address the highest priority public health risks. Regulations should be periodically reviewed at a timeframe that permits progressive improvement, to ultimately achieve long-term water quality objectives from all water supplies. The inclusion of a review clause in regulations is useful to provide a formal mechanism to ensure that regulations are reviewed regularly.

While basic principles such as adoption of WSPs and surveillance should apply to all supplies, the regulatory requirements should be tailored to reflect the size, complexity, and resource availability of drinking-water suppliers. For example, for smaller supplies WSP

requirements will be less complex and monitoring requirements will be lower, while surveillance of individual supplies will be undertaken less frequently.

Several characteristics of small water supplies require special regulatory consideration, including resources, technical capacity, laboratory capacity (e.g. geographic locations, availability of analytical equipment and associated expertise), and logistical constraints for water quality testing (e.g. accessibility issues, distances to laboratories).

Support for regulatory compliance

To deliver the intended outcomes, regulatory requirements should be supported with programmes that will help to ensure buy-in and understanding by water suppliers, which in turn will support enhanced regulatory compliance. Programmes to incentivize and facilitate achievement of regulatory requirements will also be helpful. These may include the provision of training and tools (e.g. to support WSP uptake), information campaigns, access to technical and financial supports and public recognition schemes.

Penalties or sanctions for non-compliance may be required in certain contexts, but regulations should aim to take a supportive approach above all, particularly in the case of small water supplies in recognition of the challenges they face.

Further guidance on developing context appropriate regulations in resource limited settings can be found in *Developing drinking-water quality regulations and standards* (WHO, 2018b) and *Guidelines for drinking-water quality: small water supplies* (WHO, 2024a).

24 The term "standard" is commonly used to describe a mandatory numerical value in a table of parameters and limits (such as 10 µg/L of arsenic). Regulations are requirements that can include or refer to a table of parameters and limits. Regardless of how a country defines "standards" or "regulations", both are interdependent (WHO, 2018b).

25 Other aspects of drinking-water supply should be subject to other types of regulation, including service-levels such as quantity, affordability, and reliability. Here, "regulation" refers to drinking-water quality only.

26 The most important chemicals to consider in regulations are arsenic, fluoride, lead, manganese and nitrate.

X.9 Water quality monitoring

Routine monitoring of drinking-water systems should be performed to ensure that operational processes are working effectively and that health-based targets (e.g. national drinking-water quality standards) are achieved. This chapter examines operational monitoring and compliance monitoring, including what parameters are typically monitored and for what purpose, and who is involved in the monitoring.

Operational monitoring is routine monitoring performed by water suppliers at various stages of the water supply, to determine if control measures are working properly and to inform operational decisions (e.g. optimization of chemical dose rates). Compliance monitoring is undertaken to assess if drinking-water meets regulatory standards as defined by government agencies, including verifying that the drinking-water supplied to users is safe. Compliance monitoring may be performed by water suppliers and/or external authorities (e.g. surveillance agencies). Risk assessment and management approaches (see X.5 Water safety planning) provide a systematic framework for designing site-specific monitoring programmes (WHO, 2023). The WSP approach also makes use of monitoring data to inform the reporting, interpretation and corrective actions to be taken.

The frequency and scope of water quality monitoring may also be defined by factors such as laboratory access, material supply chains, and availability of technically trained staff. Therefore, an effective and sustainable monitoring programme will be tailored to local conditions.

Operational monitoring

An operational monitoring plan must consider the parameters to target, their monitoring frequency, the critical limit (outside of which performance is deemed to be unacceptable), corrective action to be taken if a critical limit is breached, as well as data management, and data interpretation. The frequency of monitoring for each parameter should be in line with both its expected variability and the expected time interval required for an effective response. Long- and short-term variations such as equipment wear (years), seasonality (months), chemical usage (weeks), filtration cycles (days), weather events (hours), and process control (minutes) all affect the quantity and quality of water.

Many parameters may be used for operational monitoring. Some of the most common include (but are not limited to):

- **Free chlorine residual** (T.2.1 Chlorination) monitoring rapidly indicates drinking-water safety without directly measuring microbial organisms. WHO recommends a free chlorine residual concentration in the range of

0.2–0.5 mg/L, with a concentration of at least 0.2 mg/L at the point of use (WHO, 2022a). Frequent or online continuous monitoring is recommended, since chlorine concentrations can deviate on a short timescale and testing procedures are relatively cheap and simple. A common test is the dpd (diethyl para-phenylene diamine) indicator test using a comparator. For the dpd test, a tablet reagent added to a water sample changes the colour, and the strength of the colour change compared to a standard colour chart indicates both total and free chlorine residual concentration ranges. Simple test strips are also easy to use and sufficiently accurate for operational purposes in resource limited settings.

- **pH** measures the acidity or alkalinity of water. Where chlorine disinfection is practised, the pH of the water should ideally be below pH 8. To balance this and other considerations (e.g. corrosion), the optimum pH of drinking-water is in the range of pH 6.5 to 8.5, depending on the local context. pH can be measured relatively easily and inexpensively using test strips, or laboratory or field-based pH meters.
- **Turbidity** describes the cloudiness of water caused by suspended particles, chemical precipitates, organic material, and organisms. While turbidity itself does not always present a direct risk to public health, it has implications for drinking-water safety as well as aesthetic quality. The presence of turbidity may indicate that the system is vulnerable to pathogenic microorganisms due to ingress or an ineffective treatment step. High turbidity levels may also compromise consumer acceptability due to poor appearance and/or odour of the water.

Turbidity is measured in nephelometric turbidity units (NTU). For effective disinfection, turbidity should ideally be < 1 NTU. In lower resource settings (including small supplies) where this may be difficult to achieve, the aim should be to keep the turbidity below 5 NTU. Where turbidity is > 1 NTU, higher disinfection doses or contact times are required for effective disinfection (WHO, 2017c). Measuring turbidity is relatively cheap and quick on an ongoing basis. The frequency of monitoring will depend on the operational objective, because assessing performance as a key control measure within a water treatment plant (e.g. filtration step) requires continuous or frequent measurement. By comparison, routine monitoring of control measures for source water supplying the system may be less frequent if the source water turbidity typically has a low variability (WHO, 2017c).

- **Structural integrity** may be routinely monitored through system inspections, including assessing the adequacy of source protection measures, struc-

tural integrity of the intake, operational status of treatment devices, and pressure readings throughout the distribution network. Leak detection can inform repairs to reduce the risk of infiltration and back-flow. Regular inspections can also identify hygienic problems near collection taps that require awareness raising among water users. The frequency of monitoring of different structural elements varies according to expected control measures for known hazards and hazardous events. For example, detecting and addressing pipe leaks may be required on a weekly or monthly basis, whereas assessing the condition of the plinth surrounding a well may take place quarterly or annually.

Compliance monitoring

The frequencies for compliance monitoring are typically based on the population served and/or the volume of water supplied. More frequent monitoring is required for microbial parameters and less frequent for chemical parameters (WHO, 2022a). Tailored guidance for small water supplies on compliance monitoring considerations, locations and minimum frequencies according to water supply type can be found in *Guidelines for drinking-water quality: small water supplies* (WHO, 2024a).

Faecal indicator bacteria such as *Escherichia coli* (*E. coli*) or thermotolerant (faecal) coliforms are widely accepted indicators for verifying microbial safety, since the direct detection of pathogens is costly and technically challenging. Test kits currently available on the market indicate presence/absence (P/A), most probable number (MPN), or colony enumeration (in colony forming units [CFU]/100 mL). These kits offer trade-offs in terms of measurement precision, costs, incubation requirements, and training needs (Table 4). Ideally, test kits should be appropriately validated before use. For guidance on recommended minimum sample numbers and frequencies for faecal indicator testing refer to WHO 2022a and 2024a.

As a complement to *E. coli* testing, turbidity can have implications for microbial water quality and is often included as part of compliance monitoring. For chlorinated water supplies, free chlorine residual concentration and pH are also commonly monitored for the same reason.

Ideally, these three parameters should be measured when *E. coli* monitoring is conducted. However, where resources are limited, free chlorine residual monitoring should be prioritized (ideally combined with testing for turbidity and pH to confirm that chlorination conditions are optimal) to provide an indication of microbial water quality between *E. coli* monitoring events (WHO, 2024a).

Chemical contaminants from naturally occurring sources with the most significant health impacts globally are arsenic, fluoride and manganese. Other contaminants such as selenium, uranium, boron, and chromium can be a problem as well, but their presence is usually localized and limited in extent. Significant chemical contaminants from human activities or the water system itself include lead and nitrate.

The sample location and frequency should be determined by the principle source of the chemical and variability in its concentration (e.g. chemicals whose concentrations do not change significantly over time require less frequent sampling, and vice versa) (WHO, 2022a; WHO, 2018b). In general, concentrations of geogenic contaminants in groundwater, like arsenic and fluoride, vary only gradually, so may require less frequent monitoring; although, it should be noted that fluctuating groundwater levels due to seasonal variations or abstraction can mobilize contaminants, which may require more frequent monitoring.

Due to the analytical sensitivity and less frequent required monitoring intervals, chemical constituents are usually analysed in a laboratory, though field test kits are often available in regions where known hazards exist and laboratories are not easily accessed. In most countries, water sector professionals are likely to be aware of the main chemical hazards in local drinking-water. Therefore, it is important to draw on this expertise to prioritize chemical contaminants of concern and develop an effective and resource efficient monitoring programme.

Data generated from monitoring must be combined with water supply information from other sources (including information from audit findings, sanitary inspection scores, operations and maintenance information, and user feedback) to inform decisions and drive improvement. For more information, see Chapter 6 of WHO (2024a).

Test type	Cost (per-test / equipment)	Incubator required?	Training level	Precision
Presence / absence (P/A)	Low / Moderate	Yes	Low	NA
Most probable number (MPN)	High / Nil	No	Low	Low
Colony count	Low / High	Yes	High	High

NA: not applicable.

Table 4
Comparison of three test kits for detecting *E. coli* in water (after Bain et al., 2012).

X.10 Data flow and information and communication technology (ICT)

Data on water system functionality, performance, finances, and quality can be collected, analysed, and organized to improve the management, operation, and safety of urban and rural water supplies.

These data, consisting of measurements, statistics, or text, must be processed into information (defined as the knowledge gained from the data) and transferred to relevant actors to be effective. This information can then be used to monitor, manage, and improve water supplies, advocate for resources, and plan future projects.

This chapter describes how to evaluate existing information flows within water supply systems and summarizes digital data collection tools used in the water sector.

Evaluate existing information systems

Information systems comprise the tools and components for organizing and communicating information within an institution or programme, including those based on human interactions, paper, audio, and digital tools. Information and Communications Technology (ICT) are the electronic tools used to collect, organize, store, access, process, and convey data.

Before implementing a new system for collecting and managing information, it is important to evaluate existing systems. One tool for mapping these systems is the data flow diagram (DFD), an analysis method that maps inputs, processes, and outputs within a system, thereby modelling how data are collected and transferred (Fig. 9). DFDs have four elements: 1) external entities (an organization outside the system boundaries); 2) processes (transformations of or changes to data); 3) data stores (physical data storage like a notebook or computer file); and 4) data flow (transfer of data between the previous elements). These elements are captured through interviews and by observing data management. Schematics of the elements should be validated by people working within the system.

The resulting DFDs can then be used to understand existing processes (which data are collected, who is involved) and to model potential changes to the information systems. When evaluating current information systems or considering modifications, it is important to consider questions such as:

- What types of decisions can be made to maintain or improve this water system (e.g. repair water points, treat water)?
- What information is necessary for making those decisions (e.g. functional/not functional, contaminated/safe)?
- How will data be collected, and who (or what) will process and analyse the data (e.g. local extension staff, water committee, sensor)?
- Who needs to see the information to make decisions (e.g. local health staff, households)?

ICT tools for the water sector

The optimum information system will depend on the types of data to be collected (numerical, text, visual, coordinates), when it is needed (one-off, periodic, or routine; feedback or interactive system), which direction it will flow (one-way or interactive), and how it can be transmitted (manual, wireless). There are many paper- and mobile-phone-based tools for collecting information related to providing safe water. However, these were originally developed for other sectors (particularly health) and have been well-covered in other literature. Here we focus primarily on ICT tools, although these are components within broader information systems that include human actors and physical components (e.g. water points, paper), as described in the previous section.

Computers and software for word processing, managing spreadsheets, and creating presentations are now almost universal. Water system information, such as inventories, functionality, quality, or financial operations, are organized and analysed using these tools. They are frequently used for synthesizing information from multiple water systems, such as within a region or water utility.

Mapping technologies including GPS (global positioning system) for establishing the location of a water system or its components and GIS (geographic information system) to visualize and analyse location-based data are important tools in the water sector. Mobile-phone-based tools for water point mapping use GPS and camera features to inventory rural water points by collecting data about the water point and its location; previously, these activities were recorded on paper with hand-held GPS devices. Additionally, water utilities worldwide use GPS and GIS to record, map, and bill customers and track and model water distribution system components.

Mobile phones have also been used to improve water utility billing operations, such as tracking customers and issuing (and allowing payment of) water bills via mobile money, contactless payment cards, or text-based and smartphone interfaces, or to notify customers of service interruptions. Mobile phones have also been used to collect and collate the results from water quality tests, which are either entered into the phone manually or by using a phone's camera or sensors attached to the phone to record and process the results.

Finally, while most mobile phone systems rely on people to enter data, there are recent developments in automatic data collection systems, such as sensors that directly record, process, and transmit data. Examples include sensors that measure hand pump (A.2 Piston/plunger suction pump, A.3 Direct action pump, A.4 Piston pump; deep well pump) or water treatment functionality (see T. Treatment), operations, and use; asset management; water storage tank levels (D.6 Storage tanks or reservoirs); post-treatment water quality parameters (X.9 Water quality monitoring); and water production and consumption rates.

Sustainability of information systems

While information systems can improve the sustainability and operation of water systems, the information systems themselves also have to be maintained. ICTs used for developmental programmes may have

challenges, such as a lack of user engagement or a failure of the system to perform as expected or provide useful information.

With the rapid pace of technological development, new ICT tools are being constantly introduced. However, the usefulness and potential application of new tools must be evaluated as part of a holistic information system that includes many actors, technologies, and processes. Sustained functioning and the use of ICT systems can be assisted by ensuring that new tools and information systems enhance existing practices. Since data must be processed, updated, and turned into information to be useful, information systems or ICT tools should be carefully evaluated for their full life-cycle costs and weighed against potential benefits to ensure there is sufficient commitment and resources to justify such an investment.

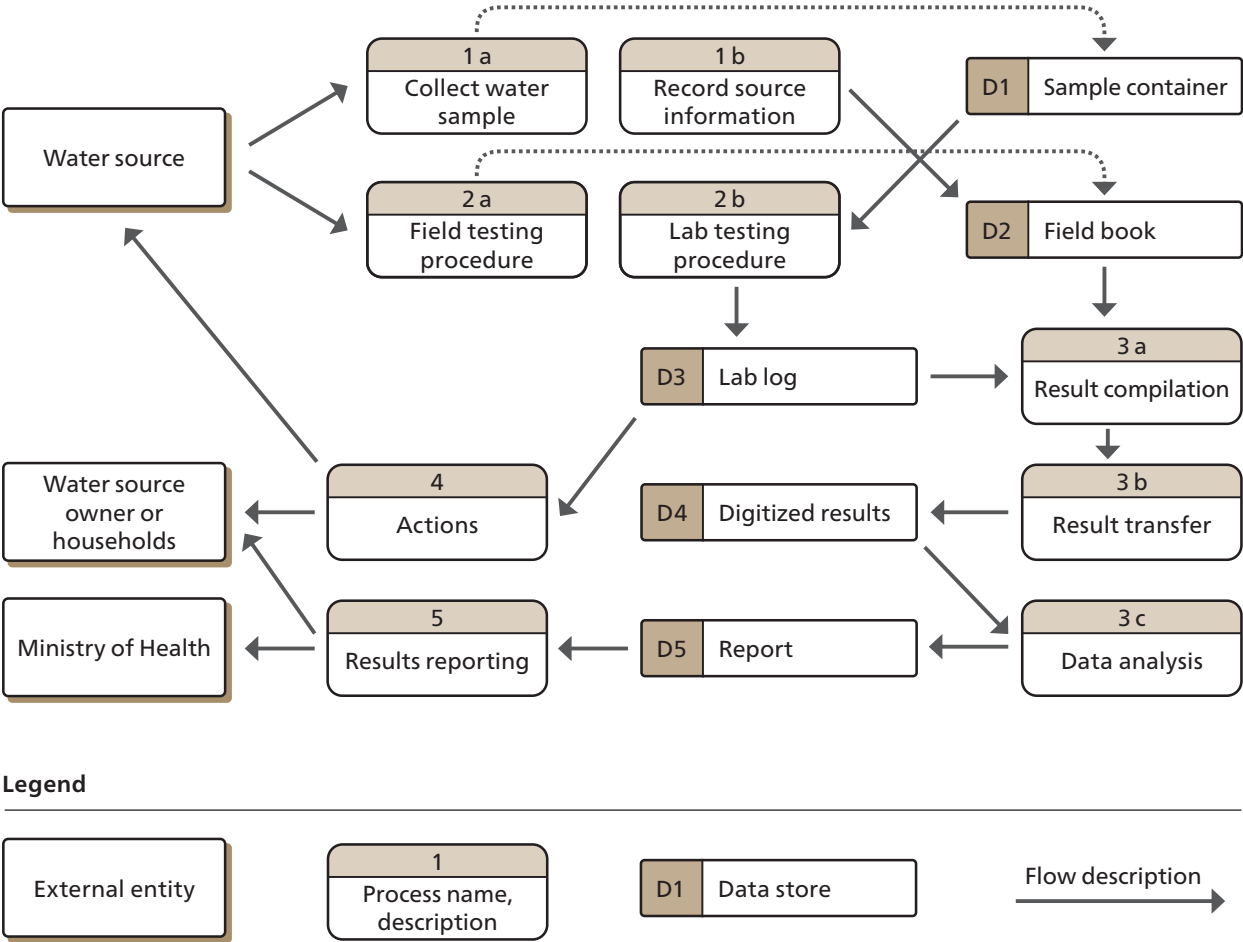


Fig. 9
An example data flow diagram (DFD) for a water quality testing programme in a monitoring agency in sub-Saharan Africa. The legend shows the four elements of the DFD.
Adapted from Kumpel et al. (2015) via <https://creativecommons.org/licenses/by/4.0/>.
© 2015 by the authors; licensee MDPI, Basel, Switzerland.

X.11 External support programmes

External support, including technical, financial and administrative assistance should be made available to resource limited water supplies. Such support is often referred to as external support programmes (ESPs), which can sustain operation and maintenance over time (Miller et al., 2019).

Many water systems, especially those serving populations with fewer than 10 000 people and those in rural areas where resources are limited (e.g. System 3: Decentralized surface water treatment, D.4 Small public and community distribution system), struggle to provide safe and sufficient drinking-water continuously over time. ESPs are designed to address these sustainability issues by providing technical, financial, and administrative assistance as well as helping with water supply conservation measures. Such support is available in low, middle, and high income countries and is often described as the “software” that supports the hardware (infrastructure). ESPs can address ageing infrastructure, intermittent service, water quality risks, operation and maintenance needs, major repairs, insufficient supply, inadequate financial management, and other threats to long-term system functionality. Consideration for ESPs should be incorporated into the planning and implementation of water supplies (X.1 Management typologies–X.3 Life-cycle and environmental impact assessment) for community-run and self-supply water systems to minimize risks (X.4 Risk assessment and risk management–X.7 Quantitative microbial risk assessment), improve monitoring, and ensure the functionality of water supply services throughout the life-cycle (X.9 Water quality monitoring and X.10 Data flow and information and communication technology).

Forms of ESPs

ESPs may be provided by government agencies, international and local NGOs, private contractors, urban utilities, community organizations, and universities. The ESPs offered by these entities can be demand or supply driven. Communities may seek out the support on an as-needed basis (demand driven), or these entities may offer unsolicited support to the community (supply driven); ESPs may also be a combination of both. For communities to be aware of the existence of ESPs, technicians may have to first approach the community. Then with time and demonstrated success, communities can come to request the support when problems occur or as information spreads about the services.

Examples of ESP typologies and activities are provided in Table 5. Large systems can also benefit from these services, but typically have more resources from

serving a large population base and may instead hire consultants or dedicated staff to fill their support needs.

The benefits and costs of ESPs

The wide-ranging benefits of ESPs were documented in a global systematic review (Miller et al., 2019) as well as in case studies from Bolivia (Plurinational State of) (Davis et al., 2008), El Salvador (Kayser et al., 2014), and Dominican Republic (Schweitzer and Mihelcic, 2012). Documented benefits reported in these studies include improvements in system performance, household satisfaction, water quality, treatment practices, financial stability, and spending on repairs and water treatment.

A challenge for ESPs is their long-term sustainability, which is often limited by insufficient funding. The cost of operating external support varies by location. A desk review of ESP per capita expenditures in seven countries found that direct support to rural communities in Latin America and Africa cost between US\$1–3 per person per year, with the successful cases reporting higher per capita expenditures (Smits et al., 2011). In El Salvador, the Asociación Salvadoreña de Sistemas de Agua (ASSA) provides technical assistance to community managed water supplies financed by fees from local water associations and international NGO support. The operating cost for the programme was US\$50 000 per year and benefited approximately 51 000 households. This cost included all Circuit Rider operating costs, support for full-time employment of five technicians, costs related to monthly community visits, water quality testing, and biannual workshops for community water committees. Costs were offset by selling chlorine tablet feeders, contributions from municipalities, household tariffs, and NGO support. External funding can decrease as beneficiaries increase the payment for service. However, most ESPs require some outside support from the municipal, state, or federal government or NGOs.

ESP outcomes can be measured by monitoring water quality, surveying water operators about operation and maintenance, tracking system finances, and monitoring customer satisfaction (see X.9 Water quality monitoring and X.10 Data flow and information and communication technology).

Example: the Circuit Rider model

In the Circuit Rider model, a single technician provides technical, financial, and operational assistance in the form of monthly visits and on-call assistance to community water systems. The model arose in the USA in the 1970s with the establishment of the National Rural Water Association (NRWA) to help rural water communities meet new water quality standards. The NRWA's

activities are financed by the federal government and through users’ fees.

Circuit Rider programmes are also found in Canada, El Salvador, Guatemala, Honduras and throughout sub-Saharan Africa. In Canada, training of First Nation or indigenous community water operators is funded by the government department for Indigenous and Northern Affairs Canada.

Table 5
Forms of external support programmes.

Technical management	Operator education and workshops on operation and maintenance, mechanical troubleshooting and repairs, water quality disinfection and dosing, water system rehabilitation and expansion, water handling and storage.
	Regular visits for water quality testing.
	On call assistance for problems that arise over time.
Financial management	Guidance in budgeting, accounting, billing, savings for future system needs, and financial transparency. Ongoing visits to check that the finances are balanced.
Administrative management	Ongoing visits to monitor and educate in national and state regulation compliance and community outreach about the quality of the service.
Water supply conservation and risk assessment	Instruction on metering, water source and watershed protection, and water safety plans.

X.12 Strengthening resilience to climate change

Water supply systems must consider and strengthen their resilience to future shocks and stresses, including those arising from climate variability and change.

Weather and climate may significantly impact water resources and public health. The supply of adequate quantities of safe drinking-water may be affected by (WHO, 2017e, p5-Eau, 2018):

- **More intense precipitation and flooding** causing increased pollutants in surface waters from run off; reduced natural attenuation in groundwater systems due to rising groundwater levels; overwhelmed water treatment systems due to reduced surface water quality; infrastructure damage to water supply systems
- **Increased drought** causing reduced drinking-water quantity; increased concentrations of pollutants (e.g. due to lower dilution factors)
- **Increased temperature** causing accelerated growth, survival, transmission, and virulence of waterborne pathogens; reduced stability of chlorine disinfectant residuals; enhanced cyanobacteria growth (e.g. toxic cyanobacterial ["algal"] blooms)
- **Sea level rise** causing increased salinity in low lying coastal aquifers; flood damage to critical assets, and infrastructure during storm surges.

Long-term planning for a safe and adequate drinking-water supply should consider uncertainties arising from climate change. Water suppliers should assess the current and projected impacts from climate change and consider what managerial, operational, and infrastructural improvements are needed to manage these risks.

Water safety planning for enhanced climate resilience

Water safety planning (see X.5 Water safety planning) offers a systematic framework to identify, assess, and manage risks from climate variability and change. The key actions of water safety planning for climate resilience include (WHO, 2017e):

- **Augment the water safety plan (WSP) team with relevant climate-related expertise.** Consider ad hoc support for the WSP team from climate-related experts, which may include climatologists, hydrologists, water resource managers, emergency response planners, water quality specialists, among others, who can help access and integrate climate-based information into the WSP.
- **Integrate relevant climate information into the water supply system description.** Available climate-related information should be accessed to understand the current and future climate projections and how this will impact the water supply system.

Examples of information sources include:

- working with stakeholders and expert groups to understand key climate threats and impacts;
 - accessing existing reports and studies (e.g. national/regional climate vulnerability assessments, water resource assessments or basin management plans); and
 - using web-based interactive portals or decision support tools.
- **Identify hazards and assess the risks.** Consider any potentially new hazards/hazardous events may be experienced in light of the climate information. Consider any changes in the risks associated with hazards and hazardous events, e.g. how climate projections may affect the effectiveness of existing control measures (if present), the likelihood of the event occurring, and the severity of the consequences.
 - **Develop a progressive improvement plan to address priority risks.** Consider what actions can be taken now and longer term to ensure stepwise improvement in system management and operation to manage the risks from climate variability and change. To manage future uncertainties, consider no-regret or low regret options that are beneficial under multiple future climate scenarios, e.g. catchment protection measures such as stock exclusion, which will provide benefits over a broad range of precipitation projections. Improvements may be considered "soft" (e.g. strengthening management procedures including emergency responses) as well as "hard" (e.g. infrastructure improvements such as flood defense barriers for critical assets) (Table 6).
 - **Develop management procedures and supporting programmes that strengthen the climate resilience of the system.** Adequate preparedness measures need to be considered for incidents, disasters, and extreme events, including flood and drought response plans. Emergency response plans that address climate-related scenarios should also be developed. These scenarios may include water quality incidents, infrastructure failure (e.g. both water supply and external infrastructure such as roads and the national grid), and planning for alternative water supplies during an emergency. Also, issues that would affect the continuity of safe drinking-water delivery during an emergency need to be managed, such as staff or essential contractor absences, or loss of supply chains for water treatment chemicals and water quality testing reagents.

Appropriate supporting programmes need to be developed to build the institutional and individual capacity of water suppliers to manage climate-related risks and provide platforms to engage with

relevant climate-related stakeholders. Examples include programmes for staff training, laboratory strengthening, stakeholder outreach, data gathering, and research and development to support climate-resilient water supplies.

Guidance for climate-resilient water safety planning in larger piped networks (e.g. Systems 2, 8, 9) can be found in *Climate resilient water safety planning* (WHO, 2017e) and *Water safety plan manual* (WHO, 2023). For smaller community supplies (e.g. Systems 5, 6), refer to *WASH climate resilient development* (UNICEF & GWP, 2015) (Table 7) and *A field guide to improving small drinking-water supplies* (WHO, 2022b). This concept can be applied to new water supply systems at the planning stage as well as to existing systems to

strengthen resilience to future anticipated events arising from climate change.

Resilience to other emergencies

Enhancing resilience to climate impacts can also support preparedness for other unforeseen impacts on water supply systems, such as natural disasters (e.g. earthquakes, conflict) and disease outbreaks (e.g. local epidemics and global pandemics). This may be achieved through improved management of staff absenteeism; ensuring continuity of supply of chemicals, reagents, and essential third-party contractors; developing emergency management and response procedures; and developing linkages to business continuity planning.

Table 6
Examples of improvement measures to manage priority risks from climate change at various stages of a water supply system.

Climate impacts	Hazardous event/hazard	Improvement measure(s) required
Increased temperature Reduced precipitation Increased drought	Reduced water quantity due to reduced rainfall and increased user demand	Catchment/source Provision of additional deep boreholes to supplement existing surface water source Treatment Filter backwash water treatment/recovery programme to minimize water wastage Distribution/storage Leak detection/mains repair programme Household User outreach and education programme on water conservation during drought Diversification of household water supply to include safe rainwater harvesting practices

Table 7

Example considerations when integrating climate aspects within water safety planning for small water supplies.

Task		Considerations to strengthen resilience
1	Engage the community and assemble a WSP team	What additional external experience/expertise is needed to support the WSP Team (e.g. local community, land users, climatologists, hydrologists, emergency planners, disaster response planners, public health specialists)?
2	Describe the water supply	What are the historical climate patterns and future projections within the water supply catchment? What part of the water supply has been/is likely to be affected by climate, and how (e.g. flooding, droughts, bushfires, landslides)?
3	Identify and assess hazards, hazardous events, existing control measures and risks	What new climate-related hazards/hazardous events may threaten the water supply system? How effective are existing control measures at controlling climate risks? What are the priority climate-related risks?
4	Develop and implement an incremental improvement plan	What strengthened or new control measures are needed to manage priority risks?
5	Monitor control measures and verify the effectiveness of the WSP	What changes may be needed to monitoring programmes (e.g. more frequent raw water turbidity checks during flood event; more frequent free chlorine residual monitoring in the network during drought/water restrictions)?
6	Carry out operations and maintenance and plan for emergencies	How may climate projections affect day-to-day operational activities? What procedures are may be needed to manage climate-related incidents and emergencies?
7	Review and improve all aspects of WSP implementation	How do changes in the water supply and/or new climate information affect the WSP? How can operational experiences and the outcomes of emergencies be used to strengthen safe drinking-water management?

References and further reading

Introduction

- Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.
- Coerver A, Ewers L, Fewster E, Galbraith D, Gensch R, Matta J, Peter M (2021). Compendium of water supply technologies in emergencies. German WASH Network (GWN), University of Applied Sciences and Arts Northwestern Switzerland (FHNW), Global WASH Cluster (GWC) and Sustainable Sanitation Alliance (SuSanA). Berlin: German WASH Network and FHNW (https://reliefweb.int/report/world/compendium-water-supply-technologies-emergencies-1st-edition?gclid=Cj0KCQjwsp6pBhCfARIsAD3GZuYMW4pgJNkAXjRd60BlonnTvVNhY6R5Et6tZue4cxorH5FkZsaaWTwaAtFhEALw_wcB, accessed 12 October 2023).
- WHO (2020). Domestic water quantity, service level and health, second edition. Geneva: World Health Organization (<https://iris.who.int/handle/10665/338044>, accessed 28 March 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).
- WHO (2024a). Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375822>, accessed 19 March 2024).

Part 1: System Templates

Introduction*

System 1 Rainwater harvesting*

- WHO (2021a). Asbestos in drinking-water: background document for development of WHO Guidelines for drinking-water quality. Geneva: World Health Organization (<https://iris.who.int/handle/10665/350932>, accessed 28 March 2023).

System 2 Centralized surface water treatment*

System 3 Decentralized surface water treatment*

System 4 Freshwater sources: manual transport combined with household water treatment and safe storage*

- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

System 6 Gravity flow supplies*

System 7 Groundwater subjected to geogenic contamination*

- WHO (2021b). Manganese in drinking-water: background document for development of WHO Guidelines for drinking-water quality. Geneva: World Health Organization (<https://iris.who.int/handle/10665/75376>, accessed 28 March 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

System 8 Freshwater sources subjected to anthropogenic contamination*

- Schmoll O, Howard G, Chilton J, Chorus I, editors (2006). Protecting groundwater for health: managing the quality of drinking-water sources. Geneva: World Health Organization (<https://iris.who.int/handle/10665/43186>, accessed 28 March 2023).
- WHO (2012a). Pharmaceuticals in drinking-water. Geneva: World Health Organization (<https://iris.who.int/handle/10665/44630>, accessed 28 March 2023).
- WHO (2016a). Protecting surface water for health: identifying, assessing and managing drinking-water quality risks in surface-water catchments. Geneva: World Health Organization (<https://iris.who.int/handle/10665/246196>, accessed 28 March 2023).

System 9 Desalination of brackish and sea water*

- WHO (2011). Safe drinking-water from desalination. Geneva: World Health Organization (<https://iris.who.int/handle/10665/70621>, accessed 28 March 2023).

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

Part 2: Technology Information Sheets

S. Source

Introduction*

- Holden R, Swanepoel R (2004). Cloud / mist harvesting. In: Introductory guide to appropriate solutions for water and sanitation. Pretoria: Department of Water Affairs and Forestry; 30–2 (Toolkit for Water Services, No. 7.2; https://www.samsamwater.com/library/Introductory_Guide_to_Appropriate_Solutions_for_Water_and_Sanitation.pdf, accessed 28 March 2023).
- Smet J, van Wijk C, editors (2002). Small community water supplies: technology, people and partnership. Delft: IRC International Water and Sanitation Center (IRC Technical Paper Series, No. 40; https://www.ircwash.org/sites/default/files/Smet-2002-Small_TP40.pdf, accessed 28 March 2023).
- SSWM (2020). Sustainable Sanitation and Water Management toolbox [website]. Willisau: Sustainable Sanitation and Water Management (<https://sswm.info/>, accessed 28 March 2023).
- WHO (2020). Domestic water quantity, service level and health, second edition. Geneva: World Health Organization (<https://iris.who.int/handle/10665/338044>, accessed 28 March 2023).
- WHO (2023). Water safety plan manual: step-by-step risk management for drinking-water suppliers, second edition. Geneva: World Health Organization (<https://iris.who.int/handle/10665/366148>, accessed 28 March 2023).
- 20for%20Domestic%20USE.pdf, accessed 28 March 2023).
- Lancaster B (2013). Rainwater harvesting for drylands and beyond, volume 1, third edition, Tucson: Rainsource Press (<https://www.harvest-ingrainwater.com/product/rainwater-harvesting-for-drylands-and-beyond-volume-1-3rd-edition-new-2019/>, accessed 28 March 2023).
- RAIN (2008). RAIN water quality guidelines: guide-lines and practical tools on rainwater quality. Amsterdam: RAIN Foundation (<https://www.pseau.org/outils/biblio/resume.php?d=4182&l=en>, accessed 28 March 2023).
- Shrestha RR (2009). Rainwater harvesting and groundwater recharge for water storage in the Kathmandu Valley. Kathmandu: International Centre for Integrated Mountain Development (Sustainable Mountain Development, No. 56; <http://lib.icimod.org/record/26764>).
- Skinner B (2022). Rainwater collection: WEDC Guide No. 43. Loughborough: WEDC (https://repository.lboro.ac.uk/articles/online_resource/GO43_Rainwater_collection/18095927/1, accessed 28 March 2023).

S.2 Groundwater*

- Alley WM, Reilly TE, Franke OL (1999). Sustainability of ground-water resources. Denver: US Geological Survey. (US Geological Survey Circular, No. 1186; <https://pubs.usgs.gov/circ/circ1186/>, accessed 28 March 2023).
- James I (2012). Borehole groundwater abstraction. Cranfield: Cranfield University on behalf of ECB, Bedford. (<https://www.yumpu.com/en/document/read/35592918/what-is-borehole-groundwater-abstraction-where-water-ecb>, accessed 28 March 2023).
- Karamouz M, Ahmadi A, Akhbari M (2011). Groundwater hydrology: engineering, planning, and management. Cleveland: CRC Press (<https://www.taylorfrancis.com/books/mono/10.1201/b13412/groundwater-hydrology-karamouz-ahmadi-akhbari>, accessed 28 March 2023).
- Kresic N, Stevanovic Z (2009). Groundwater hydrology of springs: engineering, theory, management, and sustainability. Oxford: Butterworth-Heinemann (<https://www.elsevier.com/books/groundwater-hydrology-of-springs/kresic/978-1-85617-502-9>, accessed 28 March 2023).

S.1 Rainwater*

- Casanova J, Devau N, Pettenati M (2016). Managed aquifer recharge: an overview of issues and options. In: Jakeman AJ, Barreteau O, Hunt RJ, Rinaudo J-D, Ross A, editors, Integrated ground-water management. Cham: Springer; 413–34 (https://link.springer.com/content/pdf/10.1007%2F978-3-319-23576-9_16.pdf, accessed 28 March 2023).
- Hamilton K, Reyneke B, Waso M, Clements T, Ndlovu T, Khan W et al. (2019). A global review of the microbiological quality and potential health risks associated with roof-harvested rainwater tanks. NPJ Clean Water 2(7):1–18. (<https://doi.org/10.1038/s41545-019-0030-5>).
- Hatum T, Worm JV (2006). Rainwater harvesting for domestic use. Wageningen: Agromisa Foundation, Technical Centre for Agricultural and Rural Cooperation ([https://sswm.info/sites/default/files/reference_attachments/HATUM%20and%20WORM%202006%20Rainwater%20Harvesting%](https://sswm.info/sites/default/files/reference_attachments/HATUM%20and%20WORM%202006%20Rainwater%20Harvesting%20for%20Domestic%20USE.pdf)

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

- NGWA (2013). Brackish groundwater. Westerville: National Ground Water Association (Information Brief; https://www.ngwa.org/docs/default-source/default-document-library/publications/information-briefs/brackish-groundwater.pdf?sfvrsn=62056965_2, accessed 28 March 2023).
- Sakthivadivel R (2007). The groundwater recharge movement in India. In: Giordano M, Villholth KG, editors. The agricultural groundwater revolution: opportunities and threats to development. Chennai: CAB International; 195–210 (<https://www.sciencetheearth.com/uploads/2/4/6/5/24658156/h040048.pdf>, accessed 28 March 2023).
- Schmoll O, Howard G, Chilton J, Chorus I, editors (2006). Protecting groundwater for health: managing the quality of drinking-water sources. Geneva: World Health Organization (<https://iris.who.int/handle/10665/43186>, accessed 28 March 2023).
- The Groundwater Foundation (2012). What is groundwater? [website]. Westerville: The Groundwater Foundation (<https://www.groundwater.org/get-informed/basics/whatis.html>, accessed 28 March 2023).
- Todd DK, Mays LW (1980). Groundwater hydrology. New York: Wiley (<https://www.wiley.com/en-us/Groundwater+Hydrology%2C+3rd+Edition-p-9780471059370>, accessed 28 March 2023).

S.3 Spring water*

- Hudson NW (1993). Streamflow. In: Field measurement of soil erosion and runoff. Rome: Food and Agriculture Organization of the United Nations (FAO Soils Bulletin, No. 68; http://www.fao.org/3/T0848E/t0848e-09.htm#P943_106295, accessed 28 March 2023).
- Kozisek F (2005) Health risks from drinking de-mineralised water. In: Nutrients in drinking water. Geneva: World Health Organization; 148–63 (<https://www.who.int/publications/i/item/9241593989>, accessed 28 March 2023).
- Smith M, Cross K, Paden M, Laban P, editors (2016). Spring – managing groundwater sustainably. Gland: International Union for Conservation of Nature and Natural Resources (<https://portals.iucn.org/library/sites/library/files/documents/2016-039.pdf>, accessed 28 March 2023).
- WHO (2024b). Sanitary inspection package: spring. In: Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375824>, accessed 19 March 2024).

- WHO, Robens Institute University of Surrey (1996). Springs. In: Cholera and other epidemic diarrhoeal diseases control: fact sheets on environmental sanitation. Geneva: World Health Organization (Fact Sheet 2.4; <https://www.who.int/publications/i/item/WHO-EOS-96.4>, accessed 28 March 2023).

S.4 Rivers and streams*

- Dobriyal P, Badola R, Tuboi C, Hussain SA (2017). A review of methods for monitoring streamflow for sustainable water resource management. Appl Water Sci. 7:2617–28. (<https://doi.org/10.1007/s13201-016-0488-y>).
- WHO (2016a). Protecting surface water for health: identifying, assessing and managing drinking-water quality risks in surface-water catchments. Geneva: World Health Organization (<https://iris.who.int/handle/10665/246196>, accessed 28 March 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

S.5 Ponds, lakes, and reservoirs*

- WHO (2016a). Protecting surface water for health: identifying, assessing and managing drinking-water quality risks in surface-water catchments. Geneva: World Health Organization (<https://iris.who.int/handle/10665/246196>, accessed 28 March 2023).

S.6 Brackish water, seawater*

- WHO (2011). Safe drinking-water from desalination. Geneva: World Health Organization (<https://iris.who.int/handle/10665/70621>, accessed 28 March 2023).

I. Intake

Introduction*

- SSWM (2020). Sustainable Sanitation and Water Management toolbox [website]. Willisau: Sustainable Sanitation and Water Management (<https://sswm.info/>, accessed 28 March 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

I.1 Roof water collection system*

- Hamilton K, Reyneke B, Waso M, Clements T, Ndlovu T, Khan W et al. (2019). A global review of the microbiological quality and potential health risks associated with roof-harvested rainwater tanks. *NPJ Clean Water* 2(7):1–18. (<https://doi.org/10.1038/s41545-019-0030-5>).
- Lancaster B (2013). *Rainwater harvesting for drylands and beyond*, volume 1, third edition. Tucson: Rain-source Press (<https://www.harvestingrainwater.com/product/rainwater-harvesting-for-drylands-and-beyond-volume-1-3rd-edition-new-2019/>).
- RAIN (2008). *RAIN water quality guidelines: guidelines and practical tools on rainwater quality*. Amsterdam: RAIN (<https://www.pseau.org/outils/biblio/resume.php?d=4182&l=en>, accessed 28 March 2023).
- Skinner B (2022). *Rainwater collection: WEDC Guide No. 43*. Loughborough: WEDC (https://repository.lboro.ac.uk/articles/online_resource/GO43_Rainwater_collection/18095927/1, accessed 28 March 2023).
- WHO (2024b). *Sanitary inspection package: rainwater collection and storage*. In: *Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies*. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375824>, accessed 19 March 2024).
- Worm J, van Hattum T (2006). *Rainwater harvesting for domestic use*. Wageningen: Agromisa Foundation, Technical Centre for Agricultural and Rural Cooperation (http://journeytoforever.org/farm_library/AD43.pdf, accessed 28 March 2023).

I.2 Rainwater catchment dam*

- Carlevaro F, Gonzalez C (2015). *Costing improved water supply systems for low-income communities: a practical manual*. London: IWA Publishing (<https://iwaponline.com/ebooks/book/275/Costing-Improved-Water-Supply-Systems-for-Low>, accessed 28 March 2023).
- Nissen-Petersen E (2006). *Water from small dams: a handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. Nairobi: Asal Consultants for Danish International Development Assistance (https://www.samsamwater.com/library/Book4_Water_from_Small_Dams.pdf, accessed 28 March 2023).
- Sakthivadivel R (2007). *The groundwater recharge movement in India*. In: Giordano M, Villholth KG, editors. *The agricultural groundwater revolution: opportunities and threats to development*. Chennai:

CAB International; 195–210 (<https://www.science-theearth.com/uploads/2/4/6/5/24658156/h040048.pdf>, accessed 28 March 2023).

- Stevens T (2010). *Manual on small earth dams: a guide to siting, design and construction*. Rome: Food and Agriculture Organization of the United Nations (FAO Irrigation and Drainage Paper, No. 64; <http://www.fao.org/3/i1531e/i1531e.pdf>, accessed 28 March 2023).

I.3 Sand/subsurface storage dam*

- Brikké F, Bredero M (2003). *Linking technology choice with operation and maintenance in the context of community water supply and sanitation: a reference document for planners and project staff*. Geneva: World Health Organization, Delft: IRC International Water and Sanitation Centre (<https://iris.who.int/handle/10665/42538>, accessed 28 March 2023).
- Foster S, Tuinhof A (2004). *Brazil, Kenya: subsurface dams to augment groundwater storage in basement terrain for human subsistence*. Washington (DC): World Bank Group (GW MATE Case Profile Collection, No.5; <https://documents.worldbank.org/en/publication/documents-reports/documentdetail/427471468227646169/brazil-kenya-subsurface-dams-to-augment-groundwater-storage-in-basement-terrain-for-human-subsistence>, accessed 28 March 2023).
- Vétérinaires Sans Frontières (2006). *Subsurface dams: a simple, safe and affordable technology for pastoralists*. Brussels: Vétérinaires Sans Frontières (https://www.samsamwater.com/library/Sub_surface_dams_-_a_simple_safe_and_affordable_technology_for_pastoralists.pdf, accessed 28 March 2023).

I.4 Protected spring intake*

- Meuli C, Wehrle K (2001). *Spring catchment*. St Gallen: Swiss Centre for Development Cooperation in Technology and Management (Series of Manuals on Drinking Water Supply, volume 4; https://skat.ch/wp-content/uploads/2017/01/Handbook_Volume4.pdf, accessed 28 March 2023).
- Smet J, van Wijk C, editors (2002). *Small community water supplies: technology, people and partnership*. Delft: IRC International Water and Sanitation Center (IRC Technical Paper Series, No. 40; https://www.ircwash.org/sites/default/files/Smet-2002-Small_TP40.pdf).

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). *Compendium of water systems and technologies from source to consumer*. D8.7 Water4India Horizon Report. Muttentz: FHNW.

- Smith M, Cross K, Paden M, Laban P, editors (2016). Spring – managing groundwater sustainably. Gland: International Union for Conservation of Nature and Natural Resources (<https://portals.iucn.org/library/sites/library/files/documents/2016-039.pdf>, accessed 28 March 2023).
- WHO (2024b). Sanitary inspection package: spring. In: Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375824>, accessed 19 March 2024).

I.5 Protected dug well*

- Collins S (2000). Hand-dug shallow wells. St Gallen: Swiss Centre for Development Cooperation in Technology and Management (Series of Manuals on Drinking Water Supply, volume 5; https://skat.ch/wp-content/uploads/2017/01/Handbook_Volume5.pdf, accessed 28 March 2023).
- Smith M, Cross K, Paden M, Laban P, editors (2016). Spring – managing groundwater sustainably. Gland: International Union for Conservation of Nature and Natural Resources (<https://portals.iucn.org/library/sites/library/files/documents/2016-039.pdf>, accessed 28 March 2023).
- WHO (2024b). Sanitary inspection package: dug well with a hand pump; dug well with a windlass. In: Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375824>, accessed 19 March 2024).

I.6 Protected borehole*

- Ball P (2001). Drilled wells. St Gallen: Swiss Centre for Development Cooperation in Technology and Management (Series of Manuals on Drinking Water Supply, volume 6; <https://skat.ch/wp-content/uploads/2017/01/HandbookVolume6.pdf>, accessed 28 March 2023).
- Carlevaro F, Gonzalez C (2015). Costing improved water supply systems for low-income communities: a practical manual. London: IWA Publishing (<https://iwaponline.com/ebooks/book/275/Costing-Improved-Water-Supply-Systems-for-Low>, accessed 28 March 2023).
- ICRC (2010). Technical review: borehole drilling and rehabilitation under field conditions. Geneva: International Committee of the Red Cross (https://www.icrc.org/en/doc/assets/files/other/icrc_002_0998.pdf, accessed 28 March 2023).
- Smith M, Cross K, Paden M, Laban P, editors (2016). Spring – managing groundwater sustainably. Gland: International Union for Conservation of Nature and Natural Resources (<https://portals.iucn.org/>

<library/sites/library/files/documents/2016-039.pdf>, accessed 28 March 2023).

- WHO (2024b). Sanitary inspection package: borehole with a motorized pump. In: Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375824>, accessed 19 March 2024).

I.7 River and lake water intake*

- Brikké F, Bredero M (2003). Linking technology choice with operation and maintenance in the context of community water supply and sanitation: a reference document for planners and project staff. Geneva: World Health Organization, Delft: IRC International Water and Sanitation Centre (<https://iris.who.int/handle/10665/42538>, accessed 28 March 2023).
- Lauterjung H, Schmidt G (1989). Planning of intake structures. Eschborn: Deutsche Gesellschaft für Technische Zusammenarbeit (<https://www.ircwash.org/sites/default/files/Lauterjung-1989-Planning.pdf>, accessed 28 March 2023).
- Smet J, van Wijk C, editors (2002). Small community water supplies: technology, people and partnership. Delft: IRC International Water and Sanitation Center (IRC Technical Paper Series, No. 40; https://www.ircwash.org/sites/default/files/Smet-2002-Small_TP40.pdf, accessed 28 March 2023).
- WHO (2024b). Sanitary inspection package: surface water source and abstraction. In: Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375824>, accessed 19 March 2024).

I.8 Riverbank filtration

- Gutiérrez JP, van Halem D, Rietveld L (2017). Riverbank filtration for the treatment of highly turbid Colombian rivers. *Drink Water Eng Sci*. 10: 13–26 (<https://dwes.copernicus.org/preprints/dwes-2017-10/dwes-2017-10.pdf>, accessed 28 March 2023).
- Hu B, Teng Y, Zhai Y, Zuo R, Li J, Chen H (2016). Riverbank filtration in China: a review and perspective. *J Hydrol*. 541:914–27. (<https://doi.org/10.1016/j.jhydrol.2016.08.004>).
- Jaramillo M (2012). Riverbank filtration: an efficient and economical drinking-water treatment technology. *Dyna* 79(171):148–57 (<https://www.researchgate.net/publication/>

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

260765504_Riverbank_filtration_An_efficient_and_economical_drinking-water_treatment_technology, accessed 28 March 2023).

- Smith M, Cross K, Paden M, Laban P, editors (2016). Spring – managing groundwater sustainably. Gland: International Union for Conservation of Nature and Natural Resources (<https://portals.iucn.org/library/sites/library/files/documents/2016-039.pdf>, accessed 28 March 2023).

I.9 Seawater intake*

- Mackey ED, Pozos N, James W, Seacord T (2011). Assessing seawater intake systems for desalination plants. Denver: Water Research Foundation (https://www.academia.edu/29722823/Assessing_Seawater_Intake_Systems_for_Desalination_Plants_Subject_Area_Water_Resources_and_Environmental_Sustainability, accessed 28 March 2023).
- Missimer TM, Ghaffour N, Dehwah AHA, Rachman R, Maliva RG, Amy G (2013). Subsurface intakes for seawater reverse osmosis facilities: capacity limitation, water quality improvement, and economics. *Desalination* 322:37–51. (<https://doi.org/10.1016/j.desal.2013.04.021>).
- Pankratz T (2004). An overview of seawater intake facilities for seawater desalination. In: The future of desalination in Texas, volume 2. Austin: Texas Water Development Board (<https://texaswater.tamu.edu/readings/desal/seawaterdesal.pdf>, accessed 28 March 2023).
- WaterReuse Desalination Committee (2011). Desalination plant intakes: impingement and entrainment impacts and solutions. Alexandria: WaterReuse Association (WaterReuse Association White Paper; <https://www3.epa.gov/region1/npdes/schillerstation/pdfs/AR-026.pdf>, accessed 28 March 2023).
- WHO (2011). Safe drinking-water from desalination. Geneva: World Health Organization (<https://iris.who.int/handle/10665/70621>, accessed 28 March 2023).

A. Abstraction

Introduction*

- Pump Manufacturers (2022). Directory of pump manufacturers around the world [website]. (<http://pump-manufacturers.com>, accessed 28 March 2023).
- Skat (2022). Skat: Swiss Resource Centre and Consultancies for Development [website]. St Gallen: Skat Consulting (<https://skat.ch/>, accessed 28 March 2023).

A.1 Hydraulic ram pump*

- Allspeeds (n.d.). Blake Hydram: water powered pumps. Accrington: Allspeeds Ltd. (http://www.allspeeds.co.uk/wp-content/files_mf/hydrambooklet59.pdf, accessed 28 March 2023).
- Fraenkel PL (1986). Water lifting devices. Rome: Food and Agriculture Organization of the United Nations (FAO Irrigation and Drainage Paper, No. 43; <https://www.fao.org/4/ah810e/ah810e00.htm>, accessed 28 March 2023).
- Hofkes EH, Visscher JT (1986). Renewable energy sources for rural water supply. The Hague: International Reference Centre for Community Water Supply and Sanitation (Technical Paper Series, No. 23; <https://www.ircwash.org/sites/default/files/232.0-86RE-4903.pdf>, accessed 28 March 2023).
- Jeffery TD, Thomas TH, Smith AV, Glover PB, Fountain PD (1992). Hydraulic ram pumps: a guide to ram pump water supply systems. Rugby: Practical Action Publishing (<https://practicalactionpublishing.com/book/1088/hydraulic-ram-pumps>, accessed 28 March 2023).
- Smith WB (2019). Homemade hydraulic ram pump for livestock water. Clemson: Land-Grant Press by Clemson Extension (<https://lpress.clemson.edu/publication/homemade-hydraulic-ram-pump-for-livestock-water/>, accessed 28 March 2023).
- Watt SB (1975). A manual on the hydraulic ram for pumping water. Rugby: Practical Action Publishing (<https://practicalactionpublishing.com/book/1351/a-manual-on-the-hydraulic-ram-for-pumping-water>, accessed 28 March 2023).

A.2 Piston/plunger suction pump

- Baumann E (2011). Low cost hand pumps. St Gallen: Rural Water Supply Network (Field Note, No. 2011-3; <https://www.rural-water-supply.net/en/resources/details/307>, accessed 28 March 2023).
- Smet J, van Wijk C, editors (2002). Small community water supplies: technology, people and partnership. Delft: IRC International Water and Sanitation Center (IRC Technical Paper Series, No. 40; https://www.ircwash.org/sites/default/files/Smet-2002-Small_TP40.pdf, accessed 28 March 2023).
- WEDC (1999). Low-lift irrigation pumps. In: Shaw R, editor. Running water: more technical briefs on health, water and sanitation. London: Intermediate Technology; 9–12 (Technical Brief, No. 35; <https://www.susana.org/knowledge-hub/resources?id=4145>, accessed 28 March 2023).

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

A.3 Direct action pump

- Baumann E (2011). Low cost hand pumps. St Gallen: Rural Water Supply Network (Field Note, No. 2011-3; <https://www.rural-water-supply.net/en/resources/details/307>, accessed 28 March 2023).
- Erpf K, Gomme J (2005). Mission report on the evaluation of rapid well jetting and the Canzee handpump: programme of MEDAIR in the regions of Maroantsetra and Manantenina. St Gallen: Rural Water Supply Network (<https://www.susana.org/knowledge-hub/resources?id=4195>, accessed 28 March 2023).
- Kjellerup B, Journey WK, Minnatullah KM (1989). The Tara handpump: the birth of a star. Washington (DC): World Bank (UNDP/World Bank Discussion Paper Series; <https://www.rural-water-supply.net/en/resources/details/437>, accessed 28 March 2023).
- WEDC (1999). VLOM pumps. In: Shaw R, editor. Running water: more technical briefs on health, water and sanitation. London: Intermediate Technology; 33–6 (Technical Brief, No. 41; <https://www.lboro.ac.uk/media/wwwlboroacuk/external/content/research/wedc/pdfs/technicalbriefs/41%20-%20VLOM%20pumps.pdf>, accessed 28 March 2023).

A.4 Piston pump; deep well pump

- Erpf K (2007). Installation and maintenance manual for the Afridev handpump, revision 2. St Gallen: Rural Water Supply Network (https://www.rural-water-supply.net/_ressources/documents/default/286.pdf, accessed 28 March 2023).
- Foster T, McSorley B (2016). An evaluation of the BluePump in Kenya and the Gambia. Sydney: University of Technology, Oxfam (https://www.uts.edu.au/sites/default/files/BluePump_Evaluation_Report_2016.pdf, accessed 28 March 2023).
- SKAT, RWSN (2008). Installation and maintenance manual for the India mark II handpump. St Gallen: Swiss Resource Centre for Consultancy and Development, Rural Water Supply Network (https://www.rural-water-supply.net/_ressources/documents/default/1-328-34-1384355371.pdf, accessed 28 March 2023).
- WEDC (1999). VLOM pumps. In: Shaw R, editor. Running water: more technical briefs on health, water and sanitation. London: Intermediate Technology; 33–6 (Technical Brief, No. 41; <https://www.lboro.ac.uk/media/wwwlboroacuk/external/content/research/wedc/pdfs/technicalbriefs/41%20-%20VLOM%20pumps.pdf>, accessed 28 March 2023).

A.5 Progressive cavity pump; helical rotor pump

- Baumann E (2001). Water lifting. St Gallen: Swiss Centre for Development Cooperation in Technology

and Management (Series of Manuals on Drinking Water Supply, volume 7; <https://www.rural-water-supply.net/en/resources/details/220>, accessed 28 March 2023).

- Davis J, Lambert R (2002). Engineering in emergencies: a practical guide for relief workers, second edition. London: Intermediate Technology (<https://www.susana.org/knowledge-hub/resources?id=4311>, accessed 28 March 2023).
- Smet J, van Wijk C, editors (2002). Small community water supplies: technology, people and partnership. Delft: IRC International Water and Sanitation Center (IRC Technical Paper Series, No. 40; https://www.ircwash.org/sites/default/files/Smet-2002-Small_TP40.pdf, accessed 28 March 2023).

A.6 Diaphragm pump

- Aro (n.d.). Air operated double diaphragm pumps. In: Aro [website]. Ohio: Aro. (<https://www.arozone.com/en/products/diaphragm-pumps.html>, accessed 28 March 2023). E4C (n.d.). Fraenkel PL (1986). Water lifting devices. Rome: Food and Agriculture Organization of the United Nations (FAO Irrigation and Drainage Paper, No. 43; <https://www.fao.org/4/ah810e/ah810e00.htm>, accessed 28 March 2023).
- Vergnet-hydro 60-2000 pump. In: Engineering for Change [website]. New York: Engineering for Change (www.engineeringforchange.org/solutions/product/vergnet-hydro-60-2000-pump, accessed 28 March 2023).

A.7 Rope and washer pump

- Baumann E (2011). Low cost hand pumps. St Gallen: Rural Water Supply Network (Field Note, No. 2011-3; <https://www.rural-water-supply.net/en/resources/details/307>, accessed 28 March 2023). Brand AP (2004). Meeting demand for access to safe drinking water: low-cost pump alternatives for rural communities in Honduras. Lima: Water and Sanitation Program (<https://www.rural-water-supply.net/en/resources/details/289>, accessed 28 March 2023).
- Van der Wal A, Nederstigt J (2011). Rope pump, third edition. Delft: Practica Foundation (Low Cost Pump Series; <https://www.practica.org/wp-content/uploads/Rope-pump-training-manual.pdf>, accessed 28 March 2023).
- WSP (2001). Developing private sector supply chains to deliver rural water technology. The rope pump: private sector technology transfer from Nicaragua to Ghana. Washington (DC): World Bank (<https://www.ircwash.org/sites/default/files/WSP-2001-Roepump.pdf>, accessed 28 March 2023).

A.8 Radial flow pump

- Davis J, Lambert R (2002). Engineering in emergencies: a practical guide for relief workers, second edition. London: Intermediate Technology (<https://www.susana.org/knowledge-hub/resources?id=4311>, accessed 28 March 2023).
- Pedraza A, Rosas R (2011). Evaluation of water pumping systems. Energy efficiency assessment manual, first edition. Washington (DC): Inter-American Development Bank (<https://publications.iadb.org/en/evaluation-water-pumping-systems-energy-efficiency-assessment-manual>, accessed 28 March 2023).
- Smet J, van Wijk C, editors (2002). Small community water supplies: technology, people and partnership. Delft: IRC International Water and Sanitation Center (IRC Technical Paper Series, No. 40; https://www.ircwash.org/sites/default/files/Smet-2002-Small_TP40.pdf, accessed 28 March 2023).

A.9 Axial flow pump

- Hydraulic Institute (n.d.). Standards and guidelines for pumps and pump stations [website]. Parsippany: Hydraulic Institute. (https://pumps.org/Standards_and_Guidebooks.aspx, accessed 28 March 2023).
- Stepanoff AJ (1957). Centrifugal and axial flow pumps: theory, design and application, second edition. New York: Wiley (<https://www.scribd.com/document/432281388/Centrifugal-and-Axial-Flow-Pumps-Theory-Design-and-Application>, accessed 28 March 2023).

A.10 Gravity

- Arnalich S (2009). How to design a gravity flow water system. Almería: Arnalich – Water and Habitat (<https://www.scribd.com/doc/35189494/How-to-design-a-Gravity-Flow-Water-System>, accessed 28 March 2023).
- Arnalich S (2010). Gravity flow water supply: conception, design and sizing for cooperation projects. Almería: Arnalich – Water and Habitat (<https://www.scribd.com/doc/46026759/Gravity-Flow-Water-Supply>, accessed 28 March 2023).
- Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.
- Government of India (2013). Operation and maintenance manual for rural water supplies. ministry of drinking water and sanitation. New Delhi: Ministry of Drinking Water and Sanitation (https://jalshakti-ddws.gov.in/sites/default/files/Manual_for_Operation_and_Maintenance_of_Rural_Water_Supply_Scheme.pdf, accessed 28 March 2023).

- Horst L (1975). Ground-water abstraction by gravity from sand rivers. Delft: International Courses in Hydraulic and Sanitary Engineering (Report Series, No. 13; <https://www.ircwash.org/sites/default/files/212.0-75GR-18499.pdf>, accessed 28 March 2023).
- WaterAid (2013). Gravity-fed schemes. New York: WaterAid (Technical Brief; <https://www.susana.org/knowledge-hub/resources?id=4225>, accessed 28 March 2023).

A.11 Human powered

- Goodier R (2012). Ten technologies for rural water supplies. New York: Engineering for Change (<https://www.engineeringforchange.org/news/ten-technologies-for-rural-water-supplies/>, accessed 28 March 2023).
- Government of India (2013). Operation and maintenance manual for rural water supplies. ministry of drinking water and sanitation. New Delhi: Ministry of Drinking Water and Sanitation (https://jalshakti-ddws.gov.in/sites/default/files/Manual_for_Operation_and_Maintenance_of_Rural_Water_Supply_Scheme.pdf, accessed 28 March 2023).
- Hofkes EH, editor (1981). Small community water supplies: technology of small water supply systems in developing countries. Chichester: International Reference Centre for Community Water Supply, John Wiley & Sons. (<https://www.ircwash.org/sites/default/files/201-83SM-2725.pdf>, accessed 28 March 2023).
- McJunkin FE (1977). Hand pumps for use in drinking water supplies in developing countries. The Hague: International Reference Centre for Community Water Supply (Technical Paper, No. 10; <https://www.ircwash.org/sites/default/files/232.2-77HA-8938.pdf>, accessed 28 March 2023).
- Sundaravadivel M, Vigneswaran S (2009). Rural water supply systems. In: Vigneswaran S, editor. Wastewater recycle, reuse, and reclamation, volume 2. Paris: EOLSS Publications; 56–83 (<https://www.eolss.net/ebooklib/bookinfo/wastewater-recycle-reuse-reclamation.aspx>, accessed 28 March 2023).

A.12 Wind*

- Bergey MLS (1998). Wind-electric pumping systems for communities. Oklahoma: Bergey Windpower Co. (<https://www.bergey.com/wind-school/wind-electric-pumping-systems-for-communities/>, accessed 28 March 2023).
- NREL (2022). Weather data [website]. Golden: National Renewable Energy Laboratory. (<https://energyplus.net/weather>, accessed 28 March 2023).

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

- US Department of Energy (2004). Wind power today & tomorrow. Washington (DC): Energy Efficiency and Renewable Energy (<https://www.nrel.gov/docs/fy04osti/34915.pdf>, accessed 28 March 2023).

US Department of Energy (n.d.). Installing and maintaining a small wind electric system. In: energy.gov [website]. Washington (DC): Office of Energy Efficiency & Renewable Energy (<https://www.energy.gov/energysaver/installing-and-maintaining-small-wind-electric-system>, accessed 28 March 2023).

A.13 Solar*

- Baumann E (2001). Water lifting. St Gallen: Swiss Centre for Development Cooperation in Technology and Management (Series of Manuals on Drinking Water Supply, volume 7; https://www.rural-water-supply.net/_ressources/documents/default/220.pdf, accessed 28 March 2023).
- Brikké F, Bredero M (2003). Linking technology choice with operation and maintenance in the context of community water supply and sanitation: a reference document for planners and project staff. Geneva: World Health Organization, Delft: IRC International Water and Sanitation Centre (<https://iris.who.int/handle/10665/42538>, accessed 28 March 2023).
- Holden R, Swanepoel R (2004). Introductory guide to appropriate solutions for water and sanitation. Pretoria: Department of Water Affairs and Forestry (Toolkit for Water Services, No. 7.2; https://www.samsamwater.com/library/Introductory_Guide_to_Appropriate_Solutions_for_Water_and_Sanitation.pdf, accessed 28 March 2023).
- Solar Power Authority (n.d.). How to calculate your peak sun-hours. In: Solar Power Authority [website]. (<https://www.solarpowerauthority.com/how-to-calculate-your-peak-sun-hours/>, accessed 28 March 2023).
- Van Pelt R (2007). Solar-powered groundwater pumping systems for domestic use in developing countries. Colorado: Colorado State University. (<https://studylib.net/doc/8039612/solar-powered-groundwater-pumps-for-domestic-use-in-devel%E2%80%A6>, accessed 28 March 2023).
- Van Pelt R, Weiner C, Waskom R (2012). Solar-powered groundwater pumping systems. Colorado: Colorado Water Institute (Natural Resource Series – Water, Fact Sheet, No. 6.705: <https://extension.colostate.edu/docs/pubs/natres/06705.pdf>, accessed 28 March 2023).
- September 2010. Reston: American Society of Civil Engineers (https://www.researchgate.net/publication/236592244_Feedback_Rules_for_Operation_of_Pumps_in_a_Water_Supply_System_Considering_Electricity_Tariffs, accessed 28 March 2023).
- Government of India (2013). Operation and maintenance manual for rural water supplies. ministry of drinking water and sanitation. New Delhi: Ministry of Drinking Water and Sanitation (https://jalshakti-ddws.gov.in/sites/default/files/Manual_for_Operation_and_Maintenance_of_Rural_Water_Supply_Scheme.pdf, accessed 28 March 2023).
- Pabi S, Amarnath A, Goldstein R, Reekie L (2013). Electricity use and management in the municipal water supply and wastewater industries. California: Electric Power Research Institute (https://www.sciencetheearth.com/uploads/2/4/6/5/24658156/electricity_use_and_management_in_the_municipal_water_supply_and_wastewater_industries.pdf, accessed 28 March 2023).
- Pedraza A, Rosas R (2011). Evaluation of water pumping systems: energy efficiency assessment manual. Washington (DC): Water and Sanitation Initiative, Sustainable Energy and Climate Change Initiative (<https://publications.iadb.org/en/evaluation-water-pumping-systems-energy-efficiency-assessment-manual>, accessed 28 March 2023).

A.15 Internal combustion engine – diesel and petrol

- Fraenkel P (1997). Water-pumping devices: a handbook for users and choosers. Rugby: Practical Action (<https://practicalactionpublishing.com/book/2333/water-pumping-devices>, accessed 28 March 2023).
- Government of India (2013). Operation and maintenance manual for rural water supplies. New Delhi: Ministry of Drinking Water and Sanitation (https://jalshakti-ddws.gov.in/sites/default/files/Manual_for_Operation_and_Maintenance_of_Rural_Water_Supply_Scheme.pdf, accessed 28 March 2023).
- Pabi S, Amarnath A, Goldstein R, Reekie L (2013). Electricity use and management in the municipal water supply and wastewater industries. California: Electric Power Research Institute (https://www.sciencetheearth.com/uploads/2/4/6/5/24658156/electricity_use_and_management_in_the_municipal_water_supply_and_wastewater_industries.pdf, accessed 28 March 2023).

A.14 Electric

- AbdelMeguid H, Ulanicki B (2010). Feedback rules for operation of pumps in a water supply system. Proceeding of the 12th Annual Water Distribution Systems Analysis Conference, Tucson, Arizona, 12–15

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

- SamSamWater Foundation (n.d.). SamSamWater [website]. Zaandam: SamSamWater Foundation (<http://www.samsamwater.com/>, accessed 28 March 2023).
- Smet J, van Wijk C, editors (2002). Small community water supplies: technology, people and partnership. Delft: IRC International Water and Sanitation Center (IRC Technical Paper Series, No. 40; https://www.ircwash.org/sites/default/files/Smet-2002-Small_TP40.pdf, accessed 28 March 2023).

T. Treatment

Introduction *

T.1 Clarification

T.1.1 Roughing filtration *

- Nkwonta O, Ochieng G (2009). Roughing filter for water pre-treatment technology in developing countries: a review. *Int J Phys Sci* 4(9):455–63 (<https://academicjournals.org/journal/IJPS/article-full-text-pdf/D7592EE19322>, accessed 28 March 2023).
- Wegelin M (1992). Surface water treatment by roughing filters – with special emphasis on horizontal-flow roughing filtration. Duebendorf: International Reference Centre for Waste Disposal (IRCWD Report No. 10/92; https://www.dora.lib4ri.ch/eawag/islandora/object/eawag%3A10835/datastream/PDF/Wegelin-1992-Surface_water_treatment_by_roughing-%28published_version%29.pdf, accessed 28 March 2023).
- Wegelin M (1996). Surface water treatment by roughing filters: a design, construction and operation manual. St Gallen: Swiss Centre for Development Cooperation in Technology and Management (SANDEC Report, No. 2/96; <https://www.ircwash.org/sites/default/files/Wegelin-1996-Surface.pdf>, accessed 28 March 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

T.1.2 Rapid sand filtration *

- Bruni M, Spuhler D (n.d.). Rapid sand filtration. In: SSWM platform [website]. Willisau: Sustainable Sanitation and Water Management (<https://sswm.info/sswm-university-course/module-2-centralised-and-decentralised-systems-water-and-sanitation-2/rapid-sand-filtration>, accessed 28 March 2023).
- Crittenden JC, Trussell RR, Hand DW, Howe KJ, Tchobanoglous G (2012). MWH's water treatment:

principles and design, third edition. Hoboken: John Wiley & Sons (<https://tinyurl.com/y7sxe82a>, accessed 28 March 2023).

- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).
- WHO, Robens Institute University of Surrey (1996). Rapid sand filtration. In: Cholera and other epidemic diarrhoeal diseases control: fact sheets on environmental sanitation. Geneva: World Health Organization (Fact Sheet 2.14; <https://www.who.int/publications/i/item/WHO-EOS-96.4>, accessed 28 March 2023).

T.1.3 Microfiltration *

- Peter M (2023). Membrane filtration. Oxford Research Encyclopedia of Global Public Health. (<https://doi.org/10.1093/acrefore/9780190632366.013.469>).
- Peter-Varbanets M, Zurbrugg C, Swartz C, Pronk WI (2009). Decentralized systems for potable water and the potential of membrane technology. *Water Res.* 43(2):245–65. (<https://doi.org/10.1016/j.watres.2008.10.030>).
- Pillay VL, Jacobs EP (2004). The development of small-scale ultrafiltration systems for potable water production. Durban: Water Research Commission (Water Research Commission Report, No. 1070/1/04; <http://www.wrc.org.za/wp-content/uploads/mdocs/1070-1-041.pdf>, accessed 28 March 2023).
- WHO (2017a). Potable reuse: guidance for producing safe drinking-water. Geneva: World Health Organization (<https://iris.who.int/handle/10665/258715>, accessed 28 March 2023).

T.1.4 Coagulation/flocculation/sedimentation *

- Bratby J (1980). Coagulation and flocculation with an emphasis on water and wastewater treatment. Croydon: Uplands Press Ltd (<https://www.ircwash.org/sites/default/files/253-80CO-1277.pdf>, accessed 28 March 2023).
- Bruni M, Shrestha R, Spuhler D (n.d.). Sedimentation. In: SSWM platform [website]. Willisau: Sustainable Sanitation and Water Management ([https://sswm.info/sswm-university-course/module-2-centralised-and-decentralised-systems-water-and-sanitation-2/sedimentation-\(centralised\)](https://sswm.info/sswm-university-course/module-2-centralised-and-decentralised-systems-water-and-sanitation-2/sedimentation-(centralised)), accessed 28 March 2023).

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

- Guillou M (2013). Water storage and sedimentation basins: concept and sizing. Québec: MAPAQ (https://www.agrireseau.net/agroenvironnement/documents/Fiche%20bassin%20s%C3%A9dimentationV20130729FINAL_EN%20FINAL.pdf, accessed 28 March 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

T.1.5 Coagulation/flocculation/filtration *

- Bratby J (1980). Coagulation and flocculation with an emphasis on water and wastewater treatment. Croydon: Uplands Press Ltd (<https://www.ircwash.org/sites/default/files/253-80CO-1277.pdf>, accessed 28 March 2023).
- Mazille F, Spuler D (n.d.). Coagulation-flocculation. In: SSWM platform [website]. Willisau: Sustainable Sanitation and Water Management (<https://sswm.info/water-nutrient-cycle/water-purification/hardwares/semi-centralised-drinking-water-treatments/coagulation-flocculation>, accessed 28 March 2023).

T.2 Removal/inactivation of microorganisms

T.2.1 Chlorination *

- CDC (2005). Chlorine residual testing fact sheet. Atlanta: Center for Disease Control Safe Water System Project (<http://www.ehproject.org/PDF/ehkm/cdc-chlorineresidual-updated.pdf>, accessed 28 March 2023).
- LeChevallier MW, Au KK (2004). Inactivation (disinfection) processes. In: Water treatment and pathogen control: process efficiency in achieving safe drinking water. Geneva: World Health Organization; 41–65 (<https://www.who.int/publications/i/item/9241562552>, accessed 29 March 2023).
- Lindmark M, Cherukumilli K, Crider YS, Marcenac P, Lozier M, Voth-Gaeddert L et al. (2022). Passive in-line chlorination for drinking water disinfection: a critical review. *Environ Sci Technol* 56(13):9164–9181. (<https://doi.org/10.1021/acs.est.1c08580>).
- Shrestha R, Dangol B, Spuhler D (n.d.). Chlorination. In: SSWM platform [website]. Willisau: Sustainable Sanitation and Water Management (<https://sswm.info/sswm-university-course/module-2-centralised-and-decentralised-systems-water-and-sanitation-2/chlorination>, accessed 28 March 2023).
- WHO (2017b). Principles and practices of drinking-water chlorination: a guide to strengthening chlorination practices in small- to medium-sized water supplies. New Delhi: WHO Regional Office

for South-East Asia (<https://iris.who.int/handle/10665/255145>, accessed 28 March 2023).

- WHO (2017c). Water quality and health – review of turbidity: information for regulators and water suppliers. Geneva: World Health Organization (<https://iris.who.int/handle/10665/254631>, accessed 28 March 2023).

T.2.2 On-site electrochlorination

- Casson L, Bess JW (2006). On-site sodium hypochlorite generation. *Proceedings of the Water Environment Federation* 2006(5):6335–52 (https://www.researchgate.net/publication/233710211_On-Site_Sodium_Hypochlorite_Generation, accessed 28 March 2023).
- Esposto S (2009). On-site electrochlorination application for water treatment in North Iraq. *Water Supply* 9(4):387–93. (<https://doi.org/10.2166/ws.2009.392>).
- WHO (2017c). Water quality and health – review of turbidity: information for regulators and water suppliers. Geneva: World Health Organization (<https://iris.who.int/handle/10665/254631>, accessed 28 March 2023).

T.2.3 Ultraviolet (UV) light disinfection

- Abboud N (2002). Ultraviolet disinfection for small systems. *Water Conditioning & Purification Magazine*. (<https://wcponline.com/2002/06/19/ultraviolet-disinfection-small-systems/>).
- Burch J, Thomas KE (1998). An overview of water disinfection in developing countries and the potential for solar thermal water pasteurization. Golden: National Renewable Energy Laboratory (<https://www.susana.org/knowledge-hub/resources?id=4177>, accessed 28 March 2023).
- Gadgil A, Drescher A, Greene D, Miller P, Motau C, Stevens F (1997). Field-testing UV disinfection of drinking water. In: Water and sanitation for all: partnerships and innovations. *Proceedings of the 23rd WEDC Conference*, Durban, South Africa, 1997. Loughborough: Water, Engineering and Development Centre; 153–6 (<https://wedc-knowledge.lboro.ac.uk/resources/conference/23/Gadgil.pdf>, accessed 28 March 2023).
- Water Research Center (n.d.). UV disinfection drinking water treatment. In: Know your H₂O [website]. Dallas: Water Research Center (<https://www.water-research.net/index.php/water-treatment/water-disinfection/uv-disinfection>, accessed 28 March 2023).

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

T.2.4 Slow sand filtration*

- Brikké F, Bredero M (2003). Linking technology choice with operation and maintenance in the context of community water supply and sanitation: a reference document for planners and project staff. Geneva: World Health Organization, Delft: IRC International Water and Sanitation Centre (<https://iris.who.int/handle/10665/42538>, accessed 28 March 2023).
- Huisman I, Wood WE (1974). Slow sand filtration. Geneva: World Health Organization (<https://apps.who.int/iris/handle/10665/38974>, accessed 28 March 2023).
- Logsdon G, Kohne R, Abel S, LaBonde S (2002). Slow sand filtration for small water systems. *J Env Eng Sc* 1(5):339–48. (<https://doi.org/10.1139/s02-025>).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

T.2.5 Ultrafiltration*

- Peter M (2023). Membrane filtration. Oxford Research Encyclopedia of Global Public Health. (<https://doi.org/10.1093/acrefore/9780190632366.013.469>).
- Peter-Varbanets M, Zurbrügg C, Swartz C, Pronk W (2009). Decentralized systems for potable water and the potential of membrane technology. *Water Res.* 43(2):245–65. (<https://doi.org/10.1016/j.watres.2008.10.030>).
- Pillay VL, Jacobs EP (2004). The development of small-scale ultrafiltration systems for potable water production. Durban: Water Research Commission. (Water Research Commission Report, No. 1070/1/04; <http://www.wrc.org.za/wp-content/uploads/mdocs/1070-1-041.pdf>, accessed 28 March 2023).
- WHO (2017a). Potable reuse: guidance for producing safe drinking-water. Geneva: World Health Organization (<https://iris.who.int/handle/10665/258715>, accessed 28 March 2023).

T.2.6 Pasteurization*

- Bigoni R, Krötzsch S, Sorlini S, Egli T (2014). Solar water disinfection by a parabolic trough concentrator (PTC): flow-cytometric analysis of bacterial inactivation. *J Clean Prod.* 67:62–71. (<https://doi.org/10.1046/j.1365-2672.1998.00455.x>).
- Ray C, Jain R (2014). Low cost emergency water purification technologies: Oxford: Butterworth-

Heinemann / Elsevier (Integrated Water Security Series; https://www.researchgate.net/publication/286070705_Low_Cost_Emergency_Water_Purification_Technologies_Integrated_Water_Security_Series, accessed 28 March 2023).

T.3 Treatments for geogenic contaminants

T.3.1 Fluoride removal methods*

- Fawell J, Bailey K, Chilton J, Dahi E, Fewtrell, Magara Y (2006). Fluoride in drinking-water. Geneva: World Health Organization (<https://iris.who.int/handle/10665/43514>, accessed 29 March 2023).
- Feenstra L, Vasak L, Griffioen J (2007). Fluoride in groundwater: overview and evaluation of removal methods. Utrecht: International Groundwater Resources Assessment Centre (Report No. SP 20017-1; <https://www.un-igrac.org/resource/fluoride-groundwater-overview-and-evaluation-removal-methods>, accessed 29 March 2023).
- Groundwater Assessment Platform (n.d.). Groundwater Assessment platform: Dübendorf <https://www.gapmaps.info/>, accessed 29 March 2023.
- Jagtap S, Yenkie MK, Labhsetwar N, Rayalu S (2012). Fluoride in drinking water and defluoridation of water. *Chem Rev.* 112(4):2454–66. (<https://doi.org/10.1021/cr2002855>).
- Eawag (2015). Geogenic contamination handbook – addressing arsenic and fluoride in drinking water. Johnson CA, Bretzler A, editors. Dübendorf: Swiss Federal Institute of Aquatic Science and Technology (https://www.susana.org/_resources/documents/default/3-4313-7-1621328469.pdf, accessed 29 March 2023).
- National Research Council (2006). Fluoride in drinking water: a scientific review of EPA's standards. Washington (DC): National Academies Press (<https://www.nap.edu/catalog/11571/fluoride-in-drinking-water-a-scientific-review-of-epas-standards>, accessed 29 March 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

T.3.2 Arsenic removal methods*

- Bhattacharya P, Polya DA, Jovanovic D, editors (2017). Best practice guide on the control of arsenic in drinking water. London: The International Water Association. (<https://doi.org/10.2166/9781780404929>).

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

- Feenstra L, van Erkel J, Vasak L (2007). Arsenic in groundwater: overview and evaluation of removal methods. Utrecht: International Groundwater Resources Assessment Centre (Report No. SP 2007-2; https://www.un-igrac.org/sites/default/files/resources/files/IGRAC-SP2007-2_Arsenic-removal.pdf), accessed 29 March 2023).
- Groundwater Assessment Platform (n.d.). Groundwater Assessment platform: Dübendorf <https://www.gapmaps.info/>, accessed 29 March 2023).
- Hering JG, Katsoyiannis IA, Theoduloz GA, Berg M, Hug S (2017). Arsenic removal from drinking water: experiences with technologies and constraints in practice. *J Environ Eng (New York)* 143(5):03117002, 1–9. ([https://doi.org/10.1061/\(ASCE\)EE.1943-7870.0001225](https://doi.org/10.1061/(ASCE)EE.1943-7870.0001225)).
- Eawag (2017). Geogenic contamination handbook – addressing arsenic and fluoride in drinking water. Johnson CA, Bretzler A, editors. Dübendorf: Swiss Federal Institute of Aquatic Science and Technology (<https://www.eawag.ch/en/departement/wut/projects/water-resource-quality/geogenic-contamination-handbook/>), accessed 29 March 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).
- WHO, UNICEF (2018). Arsenic primer: guidance on the investigation and mitigation of arsenic contamination. Geneva: World Health Organization, New York: UNICEF (<https://www.who.int/publications/m/item/arsenic-primer>, accessed 29 March 2023).

T.4 Treatments for organic and inorganic contaminants

T.4.1 Activated carbon*

- Çeçen F, Aktaş O (2011). Activated carbon for water and wastewater treatment: integration of adsorption and biological treatment. Weinheim: John Wiley & Sons. (<https://doi.org/10.1002/9783527639441>).
- Minnesota Department of Health (2022). Water treatment using carbon filters: GAC filter information. In: Department of Health [website]. St Paul: Minnesota Department of Health (<https://www.health.state.mn.us/communities/environment/hazardous/topics/gac.html>, accessed 29 March 2023).
- Velten S (2008). Adsorption capacity and biological activity of biological activated carbon filters in drinking water treatment [thesis]. Zürich: Eidgenössische Technische Hochschule. (<https://doi.org/10.3929/ethz-a-005820821>).

T.4.2 Ozonation

- Edzwald JK, editor (2011). Water quality & treatment: a handbook on drinking water. Denver: American Water Works Association (<https://www.accessengineeringlibrary.com/content/book/9780071630115>, accessed 29 March 2023).
- LeChevallier MW, Au K-K (2004). Inactivation (disinfection) processes. In: Water treatment and pathogen control: process efficiency in achieving safe drinking water. Geneva: World Health Organization; 41–65 (<https://www.who.int/publications/i/item/9241562552>, accessed 29 March 2023).
- Stefan MI (2018). Advanced oxidation processes for water treatment: fundamentals and applications. London: IWA Publishing. (<https://www.iwapublishing.com/books/9781780407180/advanced-oxidation-processes-water-treatment-fundamentals-and-applications>, accessed 29 March 2023).
- US EPA (1999). Wastewater technology fact sheet: ozone disinfection. Washington (DC): US Environmental Protection Agency (EPA 832-F-99-063; <https://www3.epa.gov/npdes/pubs/ozon.pdf>, accessed 29 March 2023).
- Water Research Center (n.d.). Ozonation in water treatment. In: Know your H2O [website]. Water Research Center: Dallas (<https://water-research.net/index.php/ozonation>, accessed 29 March 2023).

T.4.3 Nanofiltration*

- Radjenović J, Petrović M, Ventura F, Barceló D (2008). Rejection of pharmaceuticals in nanofiltration and reverse osmosis membrane drinking water treatment. *Water Res.* 42(14):3601–10. (<https://doi.org/10.1016/j.watres.2008.05.020>).
- Shon HK, Phuntsho S, Chaudhary DS, Vigneswaran S, Cho J (2013). Nanofiltration for water and wastewater treatment – a mini review. *Drink Water Eng Sci.* 6:47–53. (<https://doi.org/10.5194/dwes-6-47-2013>).
- Thorsen T, Flogstad H (2006). Nanofiltration in drinking water treatment – a literature review. Nieuwegein: Techneau (<https://silo.tips/download/nanofiltration-in-drinking-water-treatment>, accessed 29 March 2023).

T.5 Desalination

T.5.1 Membrane distillation*

- Alkhudhiri A, Darwish N, Hilal N (2012). Membrane distillation: a comprehensive review. *Desalination* 287: 2–18. (<https://doi.org/10.1016/j.desal.2011.08.027>).

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

T.5.2 Reverse osmosis*

- WHO (2009). Calcium and magnesium in drinking-water: public health significance. Geneva: World Health Organization (<https://iris.who.int/handle/10665/43836>, accessed 14 May 2024).
- WHO (2011). Safe drinking-water from desalination. Geneva: World Health Organization (<https://iris.who.int/handle/10665/70621>, accessed 28 March 2023).
- WHO (2017a). Potable reuse: guidance for producing safe drinking-water. Geneva: World Health Organization (<https://iris.who.int/handle/10665/258715>, accessed 28 March 2023).

D. Distribution and transport

Introduction*

D.1 Jerry cans*

- Stauffer B, Spuhler D (n.d.). Safe storage. In: SSWM platform [website]. Willisau: Sustainable Sanitation and Water Management (<https://sswm.info/water-nutrient-cycle/water-purification/hardwares/point-use-water-treatment/safe-storage>, accessed 29 March 2023).
- UN General Assembly (2010). The human right to water and sanitation: resolution adopted by the General Assembly, 3 August 2010, A/RES/64/292, available at: <https://www.refworld.org/docid/4cc926b02.html>, accessed 5 September 2023).
- WHO (2020). Domestic water quantity, service level and health, second edition. Geneva: World Health Organization (<https://iris.who.int/handle/10665/338044>, accessed 28 March 2023).
- WHO (2024b). Sanitary inspection package: household practices In: Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375824>, accessed 19 March 2024).

D.2 Water vendors (carts and trucks)*

- Kaiser S, Spuhler D (n.d.). Water vendors. In: SSWM platform: [website]. Willisau: Sustainable Sanitation and Water Management (<https://sswm.info/sswm-solutions-bop-markets/inclusive-innovation-and-service-delivery/identifying-and-realizing/water-vendors>, accessed 28 March 2023).
- Kjellén M, McGranahan G (2006). Informal water vendors and the urban poor. London: International Institute for Environment and Development (Human Settlements Discussion Paper Series; <https://tinyurl.com/53ytz65t>, accessed 28 March 2023).

- Opryszko MC, Huang H, Soderlund K, Schwab KJ (2009). Data gaps in evidence-based research on small water enterprises in developing countries. *J Water Health* 7(4):609–22. (<https://doi.org/10.2166/wh.2009.213>).
- WHO (2024b). Sanitary inspection package: filling station and water cart. In: Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375824>, accessed 19 March 2024).

D.3 Water kiosk*

- Contzen N, Marks SJ (2018). Increasing the regular use of safe water kiosk through collective psychological ownership: a mediation analysis. *J Environ Psychol.* 57:45–52. (<https://doi.org/10.1016/j.jenvp.2018.06.008>).
- Kaiser S, Spuhler D (n.d.). Water vendors. In: SSWM platform [website]: Willisau: Sustainable Sanitation and Water Management (<https://sswm.info/sswm-solutions-bop-markets/inclusive-innovation-and-service-delivery/identifying-and-realizing/water-vendors>, accessed 28 March 2023).
- Kjellén M, McGranahan G (2006). Informal water vendors and the urban poor. London: International Institute for Environment and Development (Human Settlements Discussion Paper Series; <https://tinyurl.com/53ytz65t>, accessed 29 March 2023).
- Klawitter S, Lorek S, Schaefer D, Lammerding A (2009). Case study: water kiosks. Eschborn: Deutsche Gesellschaft für Technische Zusammenarbeit (https://sswm.info/sites/default/files/reference_attachments/GTZ%202009%20CaseStudy_WaterKiosks.pdf, accessed 29 March 2023).
- Werchota R, Nordmann D (2015). Using the water kiosk to increase access to water for the urban poor in Kenya. Eschborn: Deutsche Gesellschaft für Technische Zusammenarbeit (<https://www.susana.org/en/knowledge-hub/resources-and-publications/library/details/2469>, accessed 29 March 2023).
- WHO (2024b). Sanitary inspection package: kiosk. In: Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375824>, accessed 19 March 2024).

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

D.4 Small public and community distribution systems*

- IRC (1991). Partners for progress: an approach to sustainable piped water supplies. The Hague: IRC International Water and Sanitation Centre (IRC Technical Paper Series, No. 28; <https://www.ircwash.org/resources/partners-progress-approach-sustainable-piped-water-supplies>, accessed 29 March 2023).
- Mays LW (2000). Water distribution systems handbook. New York: McGraw-Hill (<https://tinyurl.com/3pvznawa>, accessed 29 March 2023).
- Trifunovic N (2002). Water distribution. In: Smet J, van Wijk C, editors. Small community water supplies: technology, people and partnership. Delft: IRC International Water and Sanitation Center; 465–98 (IRC Technical Paper Series, No. 40; https://www.ircwash.org/sites/default/files/Smet-2002-Small_TP40.pdf, accessed 29 March 2023).
- WHO (2014). Water safety in distribution systems. Geneva: World Health Organization (<https://iris.who.int/handle/10665/204422>, accessed 29 March 2023).
- WHO (2024b). Sanitary inspection package: piped distribution: network; tapstand. In: Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375824>, accessed 19 March 2024).
- World Bank (2012). Rural water supply: design manual, volume 1. Washington (DC): World Bank Group (<http://documents.worldbank.org/curated/en/808651468144565996/Design-manual>, accessed 29 March 2023).

D.5 Centralized distribution systems*

- Mays LW (2000). Water distribution systems handbook. New York: McGraw-Hill (<https://tinyurl.com/3pvznawa>, accessed 29 March 2023).
- Swamee PK, Sharma AK (2008). Design of water supply pipe networks. New Jersey: Wiley Interscience (<https://tinyurl.com/b3sdkz4c>, accessed 29 March 2023).
- WHO (2014). Water safety in distribution systems. Geneva: World Health Organization (<https://iris.who.int/handle/10665/204422>, accessed 29 March 2023).
- WHO (2020). Domestic water quantity, service level and health, second edition. Geneva: World Health Organization (<https://iris.who.int/handle/10665/338044>, accessed 28 March 2023).
- WHO (2024b). Sanitary inspection package: piped distribution: network; tapstand. In: Sanitary inspection packages - a supporting tool for the

Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375824>, accessed 19 March 2024).

D.6 Storage tanks or reservoirs*

- WHO (2014). Water safety in distribution systems. Geneva: World Health Organization (<https://iris.who.int/handle/10665/204422>, accessed 29 March 2023).
- WHO (2024b). Sanitary inspection package: piped distribution: storage tank. In: Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375824>, accessed 19 March 2024).

H. Household water treatment and safe storage

Introduction*

H.1 Storage tanks or reservoirs*

- Graham JP, VanDerSlice J (2007). The effectiveness of large household water storage tanks for protecting the quality of drinking water. J Water Health 5(2):307–13. (<https://doi.org/10.2166/wh.2007.011b>).
- WHO (2006). Design of plumbing systems for multi-storey buildings. In: Health aspects of plumbing. Geneva: World Health Organization, World Plumbing Council; 71–84 (<https://iris.who.int/handle/10665/43423>, accessed 29 March 2023).
- WHO (2019a). Results of round II of the WHO International Scheme to Evaluate Household Water Treatment Technologies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/325896>, accessed 29 March 2023).
- WHO (2024b). Sanitary inspection package: household practices. In: Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375824>, accessed 19 March 2024).

H.2 Ceramic filtration*

- Brown J, Sobsey M (2007). Improving household drinking water quality: use of ceramic water filters in Cambodia. Phnom Penh: Water and Sanitation Program (Water and Sanitation Program Field

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

Note; http://www.potterswithoutborders.com/wp-content/uploads/2011/12/926200724252_eap_cambodia_filter.pdf, accessed 29 March 2023).

- Brown J, Sobsey M (2010). Microbiological effectiveness of locally produced ceramic filters for drinking water treatment in Cambodia. *J Water Health* 8(1):1–10. (<https://doi.org/10.2166/wh.2009.007>).
- CAWST (2009). Household water treatment and safe storage fact sheet: ceramic candle filter. Calgary: Centre for Affordable Water and Sanitation Technology (<https://tinyurl.com/pyv4we5c>, accessed 29 March 2023).
- Potters for Peace (2019). Potters for Peace [website]. Dodgeville: Good Foundations International (<https://www.pottersforpeace.org/>, accessed 29 March 2023).
- Roberts M (2003). Ceramic water purifier Cambodia field tests. Denver: International Development Enterprises (IDE Working Paper, No. 1; <https://www.susana.org/knowledge-hub/resources?id=4137>).
- Sobsey MD (2002). Managing water in the home: accelerated health gains from improved water supply. Geneva: World Health Organization (<https://iris.who.int/handle/10665/67319>, accessed 29 March 2023).
- WHO (2018a). Alternative drinking-water disinfectants: bromine, iodine and silver. Geneva: World Health Organization (<https://iris.who.int/handle/10665/260545>, accessed 29 March 2023).
- WHO (2021c). Silver in drinking-water. Background document for development of WHO Guidelines for drinking-water quality. Geneva: World Health Organization (<https://iris.who.int/handle/10665/350935>, accessed 29 March 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).
- WHO (n.d.). International Scheme to Evaluate Household Water Treatment Technologies In: World Health Organization [website]. Geneva: World Health Organization (<https://www.who.int/tools/international-scheme-to-evaluate-household-water-treatment-technologies>, accessed 29 March 2023).
- Peter-Varbanets M, Zurbrugg C, Swartz C, Pronk W (2009). Decentralized systems for potable water and the potential of membrane technology. *Water Res.* 43(2):245–65. (<https://doi.org/10.1016/j.watres.2008.10.030>).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).
- WHO (n.d.). International Scheme to Evaluate Household Water Treatment Technologies In: World Health Organization [website]. Geneva: World Health Organization (<https://www.who.int/tools/international-scheme-to-evaluate-household-water-treatment-technologies>, accessed 29 March 2023).

H.3 Ultrafiltration*

- Peter M (2023). Membrane filtration. Oxford Research Encyclopedia of Global Public Health. (<https://doi.org/10.1093/acrefore/9780190632366.013.469>).

H.4 Chemical disinfection*

- Sobsey MD, Stauber CE, Casanova LM, Brown JM, Elliott MA (2008). Point of use household drinking water filtration: a practical, effective solution for providing sustained access to safe drinking water in the developing world. *Environ Sci Technol.* 42:4261–67. (<https://doi.org/10.1021/es702746n>).
- Shrestha R, Dangol B, Spuhler D (n.d.). Chlorination. In: SSWM platform [website]. Willisau: Sustainable Sanitation and Water Management (<https://sswm.info/humanitarian-crisis/camps/water-supply/water-purification/chlorination>, accessed 29 March 2023).
- WHO (n.d.). International Scheme to Evaluate Household Water Treatment Technologies. In: World Health Organization [website]. Geneva: World Health Organization (<https://www.who.int/tools/international-scheme-to-evaluate-household-water-treatment-technologies>, accessed 29 March 2023).

H.5 Boiling*

- Brikké F, Bredero M (2003). Linking technology choice with operation and maintenance in the context of community water supply and sanitation: a reference document for planners and project staff. Geneva: World Health Organization, Delft: IRC International Water and Sanitation Centre (<https://iris.who.int/handle/10665/42538>, accessed 28 March 2023).
- Shrestha LG, Shrestha R, Spuhler D (n.d.). Boiling. In: SSWM platform [website]. Willisau: Sustainable Sanitation and Water Management (<https://sswm.info/water-nutrient-cycle/water-purification/hardwares/point-use-water-treatment/boiling>, accessed 29 March 2023).

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

- WHO (2015). Boil water. Geneva: World Health Organization (Technical Brief, WHO/FWC/ WSH/15.02; <https://iris.who.int/handle/10665/155821>, accessed 29 March, 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

H.6 Pasteurization

- Bigoni R, Krötzsch S, Sorlini S, Egli T (2014). Solar water disinfection by a parabolic trough concentrator (PTC): flow-cytometric analysis of bacterial inactivation. *J Clean Prod.* 67:62–71. (<https://doi.org/10.1016/j.jclepro.2013.12.014>).
- Ray C, Jain R (2014). Low cost emergency water purification technologies. Oxford: Butterworth-Heinemann / Elsevier (Integrated Water Security Series (<https://www.elsevier.com/books/low-cost-emergency-water-purification-technologies/ray/978-0-12-411465-4>, accessed 29 March, 2023).
- SCI (n.d.). Solar cooking around the world [website]. Sacramento: Solar Cookers International ([https://solarcooking.fandom.com/wiki/Solar_Cooking_Wiki_\(Home\)](https://solarcooking.fandom.com/wiki/Solar_Cooking_Wiki_(Home)), accessed 29 March, 2023).
- Sengar N, Dashora P, Mahavar S (2010). Low cost solar cooker: promising solution towards reducing indoor air pollution from solid fuel use. *Indian J Science Technol.* 3(10):1038–42. (https://www.solarcookers.org/files/9114/2713/2345/Low_cost_solar_cooker-Promising_solution_towards_reducing_indoor_air_pollution_from_solid_fuel_use.pdf, accessed 29 March, 2023).

H.7 Biosand filtration*

- CAWST (2012). Biosand filter construction manual. Calgary: Centre for Affordable Water and Sanitation Technology (<https://resources.cawst.org/construction-manual/a90b9f50/biosand-filter-construction-manual>, accessed 29 March, 2023).
- Hwang HG, Kim MS, Shin SM, Hwang CW (2014). Risk assessment of the Schmutzdecke of biosand filters: identification of an opportunistic pathogen in Schmutzdecke developed by an unsafe water source. *Indian J Sci Technol.* 11:2033–48. (<https://doi.org/10.3390/ijerph110202033>).
- Sobsey MD, Stauber CE, Casanova LM, Brown JM, Elliott MA (2008). Point of use household drinking water filtration: a practical, effective solution for providing sustained access to safe drinking water in the developing world. *Environ Sci Technol.* 42: 4261–67. (<https://doi.org/10.1021/es702746n>).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second

addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

H.8 Ultraviolet (UV) light disinfection

- Abboud N (2002). Ultraviolet disinfection for small systems. *Water Conditioning & Purification Magazine.* (<https://wcponline.com/2002/06/19/ultraviolet-disinfection-small-systems/>).
- Burch J, Thomas KE (1998). An overview of water disinfection in developing countries and the potential for solar thermal water pasteurization. Golden: National Renewable Energy Laboratory (<https://www.nrel.gov/docs/legosti/fy98/23110.pdf>, accessed 29 March, 2023).
- Gadgil A, Drescher A, Greene D, Miller P, Motau C, Stevens F (1997). Field-testing UV disinfection of drinking water. In: *Water and sanitation for all: partnerships and innovations. Proceedings of the 23rd WEDC Conference, Durban, South Africa, 1997.* Loughborough: Water, Engineering and Development Centre; 153–6 (<https://wedc-knowledge.lboro.ac.uk/resources/conference/23/Gadgil.pdf>, accessed 29 March, 2023).
- Parrotta MJ, Bekdash F (1998). UV disinfection of small groundwater supplies. *J Am Water Works Assoc.* 90(2):71–81. (<https://www.jstor.org/stable/41296180>, accessed 29 March, 2023).
- Water Research Center (n.d). UV disinfection. In: *Know your H2O [website].* Dallas: Water Research Center (<https://www.water-research.net/index.php/water-treatment/water-disinfection/uv-disinfection>).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

H.9 Solar water disinfection*

- Luzi S, Tobler M, Suter F, Meierhofer R (2016). SODIS manual: guidance on solar water disinfection. Dübendorf: Swiss Federal Institute of Aquatic Science and Technology (https://www.sodis.ch/methode/anwendung/ausbildungsmaterial/dokumente_material/sodismanual_2016.pdf, accessed 29 March, 2023).
- McGuigan KG, Conroy RM, Mosler H-J, du Preez M, Ubomba-Jaswa E, Fernandez-Ibañez P (2012). Solar water disinfection (SODIS): a review from bench-top to roof-top. *J Hazard Mater.* 235:29–46. (<https://doi.org/10.1016/j.jhazmat.2012.07.053>).

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

- Sobsey MD, Stauber CE, Casanova LM, Brown JM, Elliott MA (2008). Point of use household drinking water filtration: a practical, effective solution for providing sustained access to safe drinking water in the developing world. *Environ Sci Technol.* 42:4261–7. (<https://doi.org/10.1021/es702746n>).
- SODIS (2016). SODIS: safe drinking water for all [website]. Zurich: Swiss Federal Institute of Aquatic Science and Technology, Helvetas. (https://www.sodis.ch/index_EN.html, accessed 29 March, 2023).
- Spuhler D, Meierhofer R (n.d.). SODIS. In: SSWM platform [website]. Willisau: Sustainable Sanitation and Water Management (<https://sswm.info/water-nutrient-cycle/water-purification/hardwares/point-use-water-treatment/sodis>, accessed 29 March, 2023).
- WHO (2019a). Results of round II of the WHO International Scheme to Evaluate Household Water Treatment Technologies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/325896>, accessed 29 March 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).
- National Research Council (2006). Fluoride in drinking water: a scientific review of EPA's standards. Washington (DC): National Academies Press (<https://www.nap.edu/read/11571/chapter/2>, accessed 29 March, 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

H.10 Fluoride removal filters*

- Fawell J, Bailey K, Chilton J, Dahi E, Fewtrell, Magara Y (2006). Fluoride in drinking-water. Geneva: World Health Organization (<https://iris.who.int/handle/10665/43514>, accessed 29 March 2023).
- Feenstra L, Vasak L, Griffioen J (2007). Fluoride in groundwater: overview and evaluation of removal methods. Utrecht: International Groundwater Resources Assessment Centre (Report No. SP 20017-1; https://www.un-igrac.org/sites/default/files/resources/files/IGRAC-SP2007-1_Fluoride-removal.pdf, accessed 29 March, 2023).
- Groundwater Assessment Platform (n.d.). Groundwater Assessment platform: Dübendorf <https://www.gapmaps.info/>, accessed 29 March 2023).
- Jagtap S, Yenkie MK, Labhsetwar N, Rayalu S (2012). Fluoride in drinking water and defluoridation of water. *Chem Rev.* 112(4):2454–66. (<https://doi.org/10.1021/cr2002855>).
- Eawag (2017). Geogenic contamination handbook – addressing arsenic and fluoride in drinking water. Johnson CA, Bretzler A, editors. Dübendorf: Swiss Federal Institute of Aquatic Science and Technology (<https://www.eawag.ch/en/departement/wut/projects/water-resource-quality/geogenic-contamination-handbook/>, accessed 29 March 2023).
- Feenstra L, Vasak L, Griffioen J (2007). Fluoride in groundwater: overview and evaluation of removal methods. Utrecht: International Groundwater Resources Assessment Centre (Report No. SP 20017-1; https://www.un-igrac.org/sites/default/files/resources/files/IGRAC-SP2007-2_Arsenic-removal.pdf, accessed 29 March, 2023).
- Groundwater Assessment Platform (n.d.). Groundwater Assessment platform: Dübendorf <https://www.gapmaps.info/>, accessed 29 March 2023).
- Eawag (2017). Geogenic contamination handbook – addressing arsenic and fluoride in drinking water. Johnson CA, Bretzler A, editors. Dübendorf: Swiss Federal Institute of Aquatic Science and Technology (<https://www.eawag.ch/en/departement/wut/projects/water-resource-quality/geogenic-contamination-handbook/>, accessed 29 March 2023).
- Kundu DK, Mol APJ, Gupta A (2016). Failing arsenic mitigation technology in rural Bangladesh: explaining stagnation in niche formation of the Sono filter. *Water Policy* 18(6):1490–1507. (<https://doi.org/10.2166/wp.2016.014>).
- Sarkar S, Greenleaf JE, Gupta A, Uy D, SenGupta AK (2012). Sustainable engineered processes to mitigate the global arsenic crisis in drinking water: challenges and progress. *Ann Rev Chem Biomol Eng.* 3:497–517. (<https://doi.org/10.1146/annurev-chembio-eng-062011-081101>).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).
- WHO, UNICEF (2018). Arsenic primer: guidance on the investigation and mitigation of arsenic contamination. Geneva: World Health Organization, New York: UNICEF (<https://www.who.int/publications/m/item/arsenic-primer>, accessed 29 March, 2023).

H.11 Arsenic removal filters*

- Feenstra L, Vasak L, Griffioen J (2007). Fluoride in groundwater: overview and evaluation of removal methods. Utrecht: International Groundwater Resources Assessment Centre (Report No. SP 20017-1; https://www.un-igrac.org/sites/default/files/resources/files/IGRAC-SP2007-2_Arsenic-removal.pdf, accessed 29 March, 2023).
- Groundwater Assessment Platform (n.d.). Groundwater Assessment platform: Dübendorf <https://www.gapmaps.info/>, accessed 29 March 2023).
- Eawag (2017). Geogenic contamination handbook – addressing arsenic and fluoride in drinking water. Johnson CA, Bretzler A, editors. Dübendorf: Swiss Federal Institute of Aquatic Science and Technology (<https://www.eawag.ch/en/departement/wut/projects/water-resource-quality/geogenic-contamination-handbook/>, accessed 29 March 2023).
- Kundu DK, Mol APJ, Gupta A (2016). Failing arsenic mitigation technology in rural Bangladesh: explaining stagnation in niche formation of the Sono filter. *Water Policy* 18(6):1490–1507. (<https://doi.org/10.2166/wp.2016.014>).
- Sarkar S, Greenleaf JE, Gupta A, Uy D, SenGupta AK (2012). Sustainable engineered processes to mitigate the global arsenic crisis in drinking water: challenges and progress. *Ann Rev Chem Biomol Eng.* 3:497–517. (<https://doi.org/10.1146/annurev-chembio-eng-062011-081101>).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).
- WHO, UNICEF (2018). Arsenic primer: guidance on the investigation and mitigation of arsenic contamination. Geneva: World Health Organization, New York: UNICEF (<https://www.who.int/publications/m/item/arsenic-primer>, accessed 29 March, 2023).

* Adapted from Breitenmoser L, Peter M, Kazner C (2016). Compendium of water systems and technologies from source to consumer. D8.7 Water4India Horizon Report. Muttentz: FHNW.

Part 3: Cross-cutting issues

X.1 Management typologies

- Danert K (2015). Manual drilling compendium. St Gallen: Swiss Centre for Development Cooperation in Technology and Management (RWSN Publication 2015-2; <https://www.rural-water-supply.net/en/resources/details/653>, accessed 29 March, 2023).
- Lockwood H (2021). Professionalized maintenance for rural water service provision: toward a common language and vision. Sustainable WASH Systems, USAID (<https://www.globalwaters.org/resources/assets/sws/professionalized-maintenance-rural-water-service-provision-toward-common-language>, accessed 11 October 2023).
- Lockwood H, Le Gouais A (2011). Triple-S: professionalising community-based management for rural water services. The Hague: IRC International Water and Sanitation Centre (IRC Briefing Note; https://www.ircwash.org/sites/default/files/084-201502triple-s_bn01defweb_1_0.pdf, accessed 29 March, 2023).
- Marks SJ, Kumpel E, Guo J, Bartram J, Davis J (2018). Pathways to sustainability: a fuzzy-set qualitative comparative analysis of rural water supply programs. *J Clean Prod.* 205:789–98. (<https://doi.org/10.1016/j.jclepro.2018.09.029>).
- Schouten T, Moriarty P (2003). Community water, community management: from system to service in rural areas. London: ITDG Publishing (<https://practicalactionpublishing.com/book/358/community-water-community-management>, accessed 29 March, 2023).
- Sutton S (2009). An introduction to self-supply: putting the user first. Nairobi: Water and Sanitation Program – Africa (Rural Water Supply Series Field Note; <https://www.ircwash.org/sites/default/files/Sutton-2009-Introduction.pdf>, accessed 29 March, 2023).
- Sutton S, Butterworth J, Mekonta L (2012). A hidden resource: household-led rural water supply in Ethiopia. The Hague: IRC International Water and Sanitation Centre (https://www.ircwash.org/sites/default/files/a_hidden_resource_web_version_aug_2013.pdf, accessed 29 March, 2023).
- Sutton S, Harvey P (2017). Making universal access to water affordable in Zambia and Zimbabwe. In: Shaw RJ, editor. Local action with international cooperation to improve and sustain water, sanitation and hygiene (WASH) services. Proceedings of the 40th WEDC International Conference, Loughborough, UK, 24–28 July 2017 (paper 2706; <https://pdfs.semanticscholar.org/6de2/6c55a13a06770a1d1999959bc7155f93d10f.pdf>, accessed 29 March, 2023).
- Sutton S, Butterworth J (2021) Self-supply: filling the gaps in public water supply provision. Rugby, Practical Action Publishing (<https://practicalactionpublishing.com/book/2530/self-supply>, accessed 20 March 2023).
- World Bank (2017). Sustainability assessment of rural water service delivery models: findings of a multi-country review. Washington (DC): World Bank (<http://documents1.worldbank.org/curated/en/271221503692975915/pdf/Sustainability-assessment-of-rural-water-service-delivery-models-findings-of-a-multi-country-review.pdf>, accessed 29 March, 2023).
- WHO (2024a). Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375822>, accessed 19 March 2024).

X.2 Gender and inclusion

- Cairncross S (1992). Sanitation and water supply: practical lessons from the decade. Washington (DC): World Bank Group (Water and Sanitation Program Discussion Paper; <https://documents1.worldbank.org/curated/en/488891493776777098/pdf/multi-page.pdf>, accessed 29 March, 2023).
- CAP-NET, GWA (2014). Why gender matters in IWRM: a tutorial for water managers. Rio de Janeiro: International Network for Capacity Building in Integrated Water Resources Management, Dieren: Gender and Water Alliance (<https://cap-net.org/wp-content/uploads/2020/03/gender-tutorial-mid-res.pdf>, accessed 29 March, 2023).
- Gross B, van Wijk C, Mukherjee N (2000). Linking sustainability with demand, gender and poverty: a study in community-managed water supply projects in 15 countries. Washington (DC): World Bank Group (Water and Sanitation Program; <https://documents1.worldbank.org/curated/en/925451468327016238/pdf/multi0page.pdf>, accessed 29 March, 2023).
- Halcrow G, Rowland C, Willetts J, Crawford J, Carrard N (2010). Resource guide: working effectively with women and men in water, sanitation and hygiene programs. Sydney: International Women's Development Agency; Institute for Sustainable Futures, University of Technology Sydney (http://www.genderinpacificwash.info/system/resources/BAhbBIsHOgZmljoyMDExLzAxLzI0LzE5LzA0LzQyLzlkzMS9XQVNIX2ZsYXNoY2FyZHNfZmluYWw0d2ViLnBkZg/WASH_flashcards_final4web.pdf, accessed 29 March, 2023).
- Jones H, Reed B (2005). Water and sanitation for disabled people and other vulnerable groups: designing services to improve accessibility. Loughborough: WEDC (https://wedc-knowledge.lboro.ac.uk/resources/books/Water_and_Sanitation_

for_Disabled_People_-_Complete.pdf, accessed 16 October 2023).

- UNDP (2018). What does it mean to leave no one behind? New York: United Nations Development Programme (<https://www.undp.org/publications/what-does-it-mean-leave-no-one-behind>).
- United Nations (2010). The human right to water and sanitation. Geneva: United Nations General Assembly (<https://digitallibrary.un.org/record/687002?ln=en>, accessed 29 March, 2023).
- Van Houweling E (2016). "A good wife brings her husband bath water": gender roles and water practices in Nampula, Mozambique. *Soc Nat Resour*. 29(9):1065–78. (<https://doi.org/10.1080/08941920.2015.1095377>).
- WaterAid, WEDC (2013). Inclusive WASH: What does it look like? Loughborough: Water Engineering and Development Centre (https://wedc-knowledge.lboro.ac.uk/resources/learning/EI_Inclusive_WASH_what_it_looks_like_v2.pdf, accessed 29 March, 2023).
- WHO (2019b). A guide to equitable water safety planning: ensuring no one is left behind. Geneva: World Health Organization (<https://iris.who.int/handle/10665/311148>, accessed 29 March, 2023).
- WSP (2010). Gender in water and sanitation. Washington (DC): World Bank Group (Water and Sanitation Program; <https://www.wsp.org/sites/wsp.org/files/publications/WSP-gender-water-sanitation.pdf>, accessed 29 March, 2023).

X.3 Life-cycle and environmental impact assessment

- ISO 14040 (2006). Environmental management – Life cycle assessment – Principles and framework. Geneva: International Organization for Standardization (<https://www.iso.org/standard/37456.html>, accessed 29 March, 2023).
- ISO 14044 (2006). Environmental management – Life cycle assessment – Requirements and guidelines. Geneva: International Organization for Standardization (<https://www.iso.org/standard/38498.html>, accessed 29 March, 2023).
- Vince F, Aoustin E, Bréant P, Maréchal F (2008). LCA tool for the environmental evaluation of potable water production. *Desalination* 220(1–3):37–56. (<https://doi.org/10.1016/j.desal.2007.01.021>).
- Wolf M-A, Pant R, Chomkhamsri K, Sala S, Pennington D (2012). The International Reference Life Cycle Data System (ILCD) handbook. Ispra: Joint Research Centre of the European Commission (<https://eplca.jrc.ec.europa.eu/uploads/JRC-Reference-Report-ILCD-Handbook-Towards-more-sustainable-production-and-consumption-for-a-resource-efficient-Europe.pdf>, accessed 29 March, 2023).

X.4 Risk assessment and risk management

- WHO (2019c). Safe water, better health. Geneva: World Health Organization (<https://iris.who.int/handle/10665/329905>, accessed 29 March, 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

X.5 Water safety planning

- Kanyesigye C, Marks SJ, Nakanjako J, Kansime F, Ferrero G. (2019). Status of Water Safety Plan development and implementation in Uganda. *Int J Environ Res Public Health* 16(21):4096. (<https://doi.org/10.3390/ijerph16214096>).
- Kumpel E, Delaire C, Peletz R, Kisiangani J, Rinehold A, De France J et al. (2018). Measuring the impacts of Water Safety Plans in the Asia-Pacific Region. *Int J Environ Res Public Health* 15(6):1223. (<https://doi.org/10.3390/ijerph15061223>).
- Setty K, Ferrero G (2021). Water safety plans. In: Oxford Research Encyclopedia of Global Public Health. (<https://doi.org/10.1093/acrefore/9780190632366.013.338>).
- WHO (2012b). Water safety planning for small community water supplies: step-by-step risk management guidance for drinking-water supplies in small communities. Geneva: World Health Organization (<https://iris.who.int/handle/10665/75145>, accessed 29 March 2023).
- WHO (2017d). Global status report on water safety plans: a review of proactive risk assessment and risk management practices to ensure the safety of drinking-water. Geneva: World Health Organization (<https://iris.who.int/handle/10665/255649>, accessed 29 March 2023).
- WHO (2017e). Climate-resilient water safety plans: managing the health risks associated with climate variability and change. Geneva: World Health Organization (<https://iris.who.int/handle/10665/258722>, accessed 29 March 2023).
- WHO (2018c). Strengthening operations & maintenance through water safety planning: a collection of case studies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/274426>, accessed 29 March 2023).
- WHO (2019b). A guide to equitable water safety planning: ensuring no one is left behind. Geneva: World Health Organization (<https://iris.who.int/handle/10665/311148>, accessed 29 March, 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).

- WHO (2022b). A field guide to improving small drinking-water supplies: water safety planning for rural communities. Copenhagen: WHO Regional Office for Europe (<https://iris.who.int/handle/10665/363510>, accessed 29 March 2023).
- WHO (2023). Water safety plan manual: step-by-step risk management for drinking-water suppliers, second edition. Geneva: World Health Organization (<https://www.who.int/publications/i/item/9789240067691>, accessed 28 March 2023).
- WHO (2024a). Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375822>, accessed 19 March 2024).
- WHO, IWA (2022). Water safety portal [website]. Geneva: World Health Organization, London: International Water Association (<https://wsportal.org/>, accessed 29 March, 2023).
- WHO (2016b). Quantitative microbial risk assessment: application for water safety management. Geneva: World Health Organization (<https://iris.who.int/handle/10665/246195>, accessed 28 March 2023).

X.8 Drinking-water quality regulation

- Jiménez A, Saikia P, Giné R, Avello P, Leten J, Lymer BL, Schneider K, Ward R (2020). Unpacking water governance: a framework for practitioners. *Water (Switzerland)*, 12(3), 827. (<https://doi.org/10.3390/w12030827>).
- WHO (2018b). Developing drinking-water quality regulations and standards. Geneva: World Health Organization (<https://apps.who.int/iris/handle/10665/272969>, accessed 29 March, 2023).
- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).
- WHO (2024a). Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375822>, accessed 19 March 2024).

X.6 Sanitary inspections

- WHO (2012c). Rapid assessment of drinking-water quality: a handbook for implementation. Geneva: World Health Organization (<https://iris.who.int/handle/10665/331485>, accessed 28 March 2023).
- WHO (2022b). A field guide to improving small drinking-water supplies: water safety planning for rural communities. Copenhagen: WHO Regional Office for Europe (<https://iris.who.int/handle/10665/363510>, accessed 30 March 2023).
- WHO (2024a). Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375822>, accessed 19 March 2024).
- WHO (2024b). Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies. Geneva: World Health Organization (<https://iris.who.int/handle/10665/375824>, accessed 19 March 2024).

X.7 Quantitative microbial risk assessment

- CAMRA (n.d.). Quantitative microbial risk assessment (QMRA) wiki [website]. Michigan: Center for Advancing Microbial Risk Assessment (<http://qmrawiki.org/>, accessed 30 March 2023).
- Mons MN, van der Wielen JML, Blokker EJM, Sinclair MI, Hulshof KFAM, Dagendorf F et al. (2007). Estimation of the consumption of cold tap water for microbiological risk assessment: an overview of studies and statistical analysis of data. *J Water Health* 5(S1):151–70. (<https://doi.org/10.2166/wh.2007.141>).
- Schoen ME, Ashbolt NJ, Jahne MA, Garland J (2017). Risk-based enteric pathogen reduction targets for non-potable and direct potable use of roof runoff, stormwater, and greywater. *Microb Risk Anal*. 5:32–43. (<https://doi.org/10.1016/j.mran.2017.01.002>).

X.9 Water quality monitoring

- Bain R, Bartram J, Elliott M, Matthews R, McMahan L, Tung R et al. (2012). A summary catalogue of microbial drinking water tests for low and medium resource settings. *Int J Environ Res Public Health* 9(5):1609–25. (<https://doi.org/10.3390/ijerph9051609>).
- WHO (2013). Measuring chlorine levels in water supplies. Geneva: World Health Organization (Technical Note, No. 11; https://www.who.int/docs/default-source/wash-documents/wash-in-emergencies/technical-notes-on-wash-in-emergencies/who-tn-11-measuring-chlorine-levels-in-water-supplies.pdf?sfvrsn=616c5e2a_4, accessed 30 March 2023).
- WHO (2017c). Water quality and health – review of turbidity: information for regulators and water suppliers. Geneva: World Health Organization (<https://iris.who.int/handle/10665/254631>, accessed 28 March 2023).
- WHO (2017f). Operational monitoring plan development: a guide to strengthening operational monitoring practices in small- to medium-sized water supplies. New Delhi: WHO Regional Office for South-East Asia (<https://apps.who.int/iris/handle/10665/255753>, accessed 30 March 2022).
- WHO (2018b). Developing drinking-water quality regulations and standards. Geneva: World Health Organization (<https://apps.who.int/iris/handle/10665/272969>, accessed 29 March, 2023).

- WHO (2022a). Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: World Health Organization (<https://iris.who.int/handle/10665/352532>, accessed 28 March 2023).
- WHO (2023). Water safety plan manual: step-by-step risk management for drinking-water suppliers, second edition. Geneva: World Health Organization (<https://www.who.int/publications/i/item/9789240067691>, accessed 28 March 2023).
- Schweitzer R, Mihelcic JR (2012). Assessing sustainability of community management of rural water systems in the developing world. *J Water Sanit Hyg Dev.* 2(1):20–30. (<https://doi.org/10.2166/washdev.2012.056>).
- Smits S, Verhoeven J, Moriarty PB, Fonseca C, Lockwood H (2011). Arrangements and cost of providing support to rural water service providers. The Hague: IRC International Water and Sanitation Centre (WASHCost Global Working Paper, No. 5; https://www.ircwash.org/sites/default/files/working_paper_5_-_arrangements_and_cost_of_providing_support_to_rural_water_service_providers_analyses.pdf, accessed 30 March 2023).

X.10 Data flow and information and communication technology (ICT)

- Hutchings M, Dev A, Palaniappan M, Srinivasan V, Ramanathan N, Taylor J (2012). mWASH: mobile phone applications for the water, sanitation, and hygiene sector. Oakland: Pacific Institute (<https://pacinst.org/wp-content/uploads/2012/05/mwash.pdf>, accessed 30 March 2023).
- Kazadi J, Kleemeier E (2011). Mobile phones and water point mapping. Rural Water Supplies Collaborative. Washington (DC): World Bank (Quick Read, Issue No. 1; <https://openknowledge.worldbank.org/handle/10986/11058>, accessed 30 March 2023).
- Kumpel E, Peletz R, Bonham M, Fay A, Cock-Eteb A, Khush R (2015). When are mobile phones useful for water quality data collection? An analysis of data flows and ICT applications among regulated monitoring institutions in sub-Saharan Africa. *Int J Environ Res Public Health* 12(9):10846–60. (<https://doi.org/10.3390/ijerph120910846>).
- Thompson P, Hope R, Foster T (2012). Is silence golden? Of mobiles, monitoring, and rural water supplies. *Waterlines* 31(4):280–92 (<https://www.jstor.org/stable/pdf/24686816.pdf?refreqid=excelsior%3A0597be3c0288fcdddf742f2d493433a8>, accessed 30 March 2023).

X.11 External support programmes

- Davis J, Lukacs H, Jeuland M, Alvestegui A, Soto B, Lizárraga G et al. (2008). Sustaining the benefit of rural water supply investments: Experiences from Cochabamba and Chuquisaca, Bolivia. *Water Resour Res.* 44(12). (<https://doi.org/10.1029/2007WR006550>).
- Kayser GL, Moomaw W, Portillo et al. (2014). Circuit rider post-construction support: improvements in domestic water quality and system sustainability in El Salvador. *J Water Sanit Hyg Dev.* 4(3):460–70. (<https://doi.org/10.2166/washdev.2014.136>).
- Miller M, Cronk R, Klug T, Kelly ER, Behnke N, Bartram J (2019). External support programs to improve rural drinking water service sustainability: a systematic review. *Sci Total Environ.* 670:717–31. (<https://doi.org/10.1016/j.scitotenv.2019.03.069>).

X.12 Climate-resilient water supply

- pS-Eau (2018). WASH services and climate change: impacts and responses. Paris: Programme Solidarité Eau (<https://www.pseau.org/en/wash-climate-change>, accessed 30 March 2023).
- UNICEF, Global Water Partnership (2015). WASH climate resilient development. Technical brief: Local participatory water supply and climate change risk assessment: modified water safety plans. New York: UNICEF, Stockholm: Global Water Partnership (https://www.gwp.org/globalassets/global/about-gwp/publications/unicef-gwp/gwp_unicef_tech_a_web.pdf, accessed 30 March 2023).
- WHO (2017e). Climate-resilient water safety plans: managing the health risks associated with climate variability and change. Geneva: World Health Organization (<https://iris.who.int/handle/10665/258722>, accessed 29 March 2023).
- WHO (2023). Water safety plan manual: step-by-step risk management for drinking-water suppliers, second edition. Geneva: World Health Organization (<https://www.who.int/publications/i/item/9789240067691>, accessed 28 March 2023).
- UNICEF & GWP (2015). Local participatory water supply and climate change risk assessment: modified water safety plans. New York: UNICEF (https://www.gwp.org/globalassets/global/about-gwp/publications/unicef-gwp/gwp_unicef_tech_a_web.pdf, accessed 19 June 2023).

Annex 1: Approach to content development and declarations of interest

The World Health Organization (WHO) recognized the need for updated guidance on drinking-water systems and technologies as part of the development of WHO's *Guidelines for drinking-water quality: small water supplies*.²⁷

A first draft of the publication was developed between 2015 and 2017 by select experts in the sphere of drinking-water systems, technological interventions, and related cross-cutting issues including costing, risk management, and monitoring. The drinking-water systems and technologies were selected based on expert experiences of the most common and conventional system and technology types that were globally applicable. The treatment technologies covered in this publication are broadly aligned with the treatment interventions presented in WHO's *Guidelines for drinking-water quality*.²⁸

Targeted peer reviews were conducted by select experts between 2017–18. From 2019, this draft was further revised during successive rounds of updates to address peer review feedback, wider aspects of the enabling environment, and ensure greater alignment

with key recommendations in related WHO publications, including the *Guidelines for drinking-water quality*. This was followed by a subsequent round of peer review by experts and practitioners, additional development including incorporating key recommendations from related WHO guidance, including the *Guidelines for drinking-water quality: small water supplies*, and finalized in 2025. The selection of drinking-water systems and technologies was explicitly highlighted as an area for feedback during the peer review stages, and subsequently validated as appropriate by the peer review process. Collectively input was obtained representing countries across all 6 WHO regions.

All technical editors submitted declarations of interest to WHO to disclose any potential conflicts of interest that might affect, or reasonably be perceived to affect, their objectivity and independence in relation to the subject matter of this publication. WHO reviewed each of the declarations and concluded that none could give rise to a potential or reasonably perceived conflict of interest related to the subjects covered by this publication.

²⁷ WHO (2024). *Guidelines for drinking-water quality: small water supplies*. Geneva, World Health Organization (<https://iris.who.int/handle/10665/375822>).

²⁸ WHO (2022). *Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda*. Geneva, World Health Organization (<https://iris.who.int/handle/10665/352532>).

Annex 2: Summary of select intake and treatment interventions to support safe drinking-water supply management

Delivery of safe and reliable drinking-water requires the selection of context-appropriate interventions throughout the water supply. Table A2.1 provides a summary of common technological interventions at the intake, central water treatment plant and user level components of a water supply chain. In designing water treatment trains, careful consideration must be given to many context-specific factors, including the following.

- **Source water quality:** The type of water source (e.g. groundwater, surface water, rainwater) and initial quality of the source, including parameters such as turbidity, pH, hardness, and presence of specific contaminants, informs the type and extent of treatment required
- **Contaminant profile:** Identification of specific contaminants likely to be present in the water, such as pathogens (viruses, bacteria and/or protozoa/helminths), organic compounds, heavy metals, or dissolved solids, guides the selection of treatment processes targeted at their removal or reduction.
- **Regulatory requirements:** Compliance with national drinking-water quality standards and regulations influences the choice of treatment processes and their performance criteria (see X.8 Drinking-water quality regulation).
- **Cost:** When costing potential interventions, financial considerations should span short- to long-term costs, as well as appropriate financing mechanisms. Costs may include capital costs, operation and maintenance costs (including power, consumables, personnel, support systems), costs of future upgrades, costs of regulatory compliance.
- **Infrastructure and space constraints:** Consideration of available space, existing infrastructure, and operational limitations may impact the selection of treatment technologies and the layout of treatment units within the treatment train.
- **Operational and maintenance considerations:** Factors such as ease of operation and maintenance requirements, availability of skilled personnel, influence the feasibility and sustainability of chosen treatment processes (see also Cost above). Careful consideration must be given to the energy requirements and the reliability of power sources, as well as critical supply chains e.g. spare parts, treatment chemicals/additives, testing reagents.
- **Environmental considerations:** Assessment of potential environmental impacts, such as energy consumption, chemical usage, waste generation, and byproduct disposal, informs the selection of environmentally sustainable treatment options.
- **Community preferences and stakeholder engagement:** Input from stakeholders, including community members, local authorities, and water suppliers helps to align treatment selection with community preferences, needs, and priorities.
- **Resilience to shocks and stressors:** Current and likely future threats within a water supply (e.g. from natural disasters, climate affects such as flooding and drought, conflict, migration, changes in catchment land use), to inform the selection technologies for resilience.
- **Provision of equitable services:** By explicitly considering all users of the water supply at the intervention selection stage, including those disadvantaged, decision-makers can help to ensure that safe and adequate water is accessible to all members of society, regardless of socioeconomic status or background.

Selecting drinking-water source protection or treatment interventions requires consultation with experts, including engineers, public health representatives, drinking-water quality regulators, and catchment agencies. Consultation with select stakeholders should also be considered e.g. climatologists, disaster and emergency representatives, hydro(geo)ologists, non-governmental organizations, user groups, disability/disadvantaged groups and other organizations responsible for supporting safe drinking-water programmes within a country.

Throughout the water supply, due attention should also be given to ensuring multiple barriers are in place, that is, where one barrier (or control measure) fails, other barriers should help to ensure the safety of the drinking-water supply to the user. Attention should also be given to the overall performance of the water supply as part of water safety plan (WSP) implementation, recognizing individual interventions may be influenced by the combination of interventions applied.

Table A2.1 Characteristics and application of common interventions at the intake²⁹

Intervention	Aim	Key benefits	Key limitations	Construction/ purchasing	Operations and maintenance	Monitoring ³⁰	Cost	Water characteristics typical for application
Roofwater collection system (I.1)	Protection against contamination. Ensuring adequate water quantity.	Passive collection with no operational energy requirement. Typically low organic contaminants present in the collected water. Can reduce stormwater runoff. Low risk of vector breeding provided storages have fitted roofs, and entry points are fitted with mosquito-proof screening.	Quality of water depends on factors that include the quality of rainwater, presence of avian faeces and airborne contaminants from local activities (e.g. slurry spreading, crop spraying) on the roof collection system, and the type and condition of the roof catchment materials (e.g. roof, guttering channel material). Where there is a risk of microbial contamination, treatment/disinfection before consumption is required. Systems generally have a limited storage capacity, and rely on adequate rainfall for year-round supply. Requires diversion of the first flush of rainwater.	Technical assistance needed for design and construction. Construction (and repair) are simple.	Routine inspection/cleaning are simple, and typically include the roof catchment, gutters, filter box, first-flush device. Periodic cleaning and disinfection of the storage tank is required to remove accumulated sludge.	Visual inspection.	Low, but costs can vary depending on material and size of collectors, location, and access.	No water quality requirements, but airborne contaminants could contaminate the water supply.
Rainwater catchment dam (I.2)	Ensuring adequate water quantity.	Potential to store larger volumes of water, year-round with ease of access. Can reduce microbial and particulate contamination through natural processes (e.g. sunlight [UV] inactivation, predation, sedimentation).	Subject to contamination (e.g. via surface water run-off). Wildlife presence could negatively impact microbial quality. Stagnant water may contribute to algal (cyanobacterial) growth, and promote mosquito breeding. Requires treatment and disinfection before consumption. Water losses may occur from seepage and evaporation. Sediment builds up, decreasing storage capacity over time.	Expert knowledge needed for sizing, location and design. Technical assistance needed for developing buffer zones around the reservoir to protect water quality. Typically long life-span.	Routine valve operation to control flows, including controlled water release during heavy/prolonged rainfall. Periodic sediment removal. Routine inspection and maintenance to prevent dam failure.	Visual inspection. Monitoring for polluting activities within exclusion zones (if in place).	Low, but costs can vary depending on size and land availability.	No special requirements.

²⁹ For interventions that may be applied at the source (i.e. sections 5.1 to 5.6 of this publication), refer to *Protecting groundwater for health: managing the quality of drinking-water sources*. Geneva, World Health Organization; 2006, and *Protecting surface water for health: identifying, assessing and managing drinking-water quality risks in surface-water catchments*. Geneva, World Health Organization; 2016.

³⁰ Unless otherwise stated, monitoring in this context refers to operational monitoring to ensure interventions (or "control measure") continue to operate within acceptable limits (refer to X.9 Water quality monitoring). In addition to the monitoring activities listed, periodic sanitary inspection and water quality monitoring should also be performed where applicable.
For more information, see *Guidelines for drinking-water quality: small water supplies and Sanitary inspection packages - a supporting tool for the Guidelines for drinking-water quality: small water supplies*. Geneva, World Health Organization; 2024.

Intervention	Aim	Key benefits	Key limitations	Construction/ purchasing	Operations and maintenance	Monitoring ³⁰	Cost	Water charac- teristics typical for application
Sand or sub- surface storage dam (1.3)	Protection against contamination. Ensuring adequate water quantity.	Natural filtration can result in higher quality water than surface dams. Typically no water loss through evaporation.	Requires appropriate sites (e.g. sand storage dams require a steep slope; subsurface storage dams require a flat area) which may be far from users to access or be prohibitively expensive to achieve. Dissolved chemicals or nutrients and some pathogens (viruses) may get into the water during seepage. May require treatment/dis- infection before consumption. Water loss may occur from seepage.	Expert knowledge needed for design and construction. Construction (and repair) can use locally-available materials. Typically long life-span.	Minimal operations and maintenance required if properly constructed. Periodic sediment removal. Associated wells or gravity pipes should be inspected and maintained routi- nely.	Visual inspection. Groundwater-level monitoring. Monitoring for polluting activities within exclusion zones (if in place).	Low, although construction is labour-in- tensive and can vary depending on size and site approp- riateness.	No special requirements.
Protected spring intake (1.4)	Protection against contamination. Ensuring adequate water quantity.	Source protection (depends on local conditions). No pumping required if fed by gravity. Simple and robust design.	Water quality and quantity depends on local conditions. May require treatment/disin- fection before consumption.	Expert knowledge nee- ded for placement and design. Construction (and repair) are simple, and can use locally-available materials.	Routine inspection, maintenance and repair of spring box, security features, and associated infrastructure/equip- ment. Periodic sediment remo- val and disinfection of the spring box.	Visual inspection. Flow rate moni- toring. Monitoring for polluting activities within exclusion zones (if in place).	Low, parti- cularly if no pumping required.	No special requirements.
Protected dug well (1.5)	Protection against contamination. Ensuring adequate water quantity.	Source protection (depends on local conditions). Yield (quantity) can be increased by well deepening/ widening.	Water quality and quantity depends on local conditions. May require treatment/disin- fection before consumption.	Expert knowledge needed for locating and construction. Const- ruction (and repair) can use locally-available materials.	Routine inspection, main- tenance and repair of well head, and associated infrastructure and equip- ment (e.g. hand pump). Periodic sediment remo- val and disinfection.	Visual inspection. Water-level moni- toring. Monitoring for polluting activities within exclusion zones (if in place).	Low.	No special requirements.
Protected borehole (1.6)³¹	Protection against contamination. Ensuring adequate water quantity.	Source protection (depends on local conditions). Deeper boreholes typically have better water quality (e.g. relative to shallower dug wells).	Water quality (including geogenic contaminants such as arsenic and fluoride) and quantity depends on local conditions. Salinity may be an issue (e.g. in low-lying coastal areas, particu- larly where there is overextraction occurring). May require treatment/disin- fection before consumption.	Expert knowledge nee- ded for locating, drilling, grouting, and finishing the borehole. Construction for the protection of the head of the borehole, (and repair) is simple. Typically long life-span.	Routine inspection, repair of borehole head, security features, and associated infrastructure/equipment (e.g. motorized pump, which requires access to additional tools/parts.) Periodic sediment remo- val and disinfection.	Visual inspection. Water-level moni- toring. Monitoring water production and pump maintenance Monitoring for polluting activities within exclusion zones (if in place).	Low to moderate depending on local conditions.	No special requirements.

³¹ Information also applies to protected tubewells.

Intervention	Aim	Key benefits	Key limitations	Construction/ purchasing	Operations and maintenance	Monitoring ³⁰	Cost	Water characteristics typical for application
River and lake water intake (1.7)	Protection against contamination and prevention of damage (e.g. from aquatic organisms, gravel) to downstream elements of the water supply. Ensuring adequate water quantity.	Use of variable intake heights can selectively abstract higher quality water (e.g. avoiding surface algal scums). Simple and robust structures, easy to operate.	Abstracted water is subject to contamination if located downstream of polluting activities (e.g. agriculture, wastewater or stormwater discharges). Flood events can clog/damage infrastructure. May require a weir to facilitate abstraction during low flow/drought events. Requires treatment/disinfection before consumption.	Expert knowledge typically needed for choosing optimal location, intake size, strainer/screen configuration, and for construction.	Routine inspection and maintenance of strainer, screens (e.g. to prevent clogging). Valve operation and maintenance. Routine sediment/aquatic plant removal around the intake. More frequent inspection may be required during severe weather events.	Visual inspection. Flow rate monitoring. Monitoring for polluting activities within exclusion zones (if in place).	Low to moderate depending on configuration and local factors.	Applicable to waters free from intake-clogging species (e.g. invasive mussels, aquatic weeds).
Riverbank filtration (1.8)	Protection against contamination. Ensuring adequate water quantity.	Simple system and operation. Effective exclusion of particles causing turbidity, and can reduce concentrations of microbial pathogens (enteric viruses, bacteria and protozoa/helminths) and organic compounds.	Quality of the filtered water depends on local conditions (e.g. soil type). Pathogen reduction, particularly for bacteria and viruses, may be compromised if coarse riverbed sediments are present. May not be feasible to apply where the river bed is clay-based. Under certain conditions, filtered water may contain iron and manganese. May require additional treatment/disinfection before consumption.	Expert knowledge needed for choosing optimal location, pipe size, and filtration material. Simple construction.	Periodic system flushing. Addressing clogging issues if they arise.	Visual inspection. Flow rate inspection. Monitoring for polluting activities within exclusion zones (if in place).	Low.	No special requirements.
Seawater intake (1.9)	Protection against contamination and prevention of damage (e.g. from aquatic organisms, vegetative material, sand) to downstream elements of the water supply. Ensuring adequate water quantity.	Surface intakes can abstract large volumes of water at low cost. Subsurface intakes naturally pre-treat the sea water (e.g. removal of particulates, organic compounds, aquatic organisms).	Surface intakes may harm aquatic organisms. Subsurface intakes require a minimum sediment layer for natural filtration, the efficacy of which can be impacted by beach erosion. Subsurface intakes may also impact nearby fresh groundwater aquifers. Requires treatment (including removal of salts) and disinfection before consumption.	Expert knowledge typically needed for choosing optimal location, intake size, strainer/screen configuration, and construction. Typically long life-span.	Periodic cleaning of surface intakes (e.g. air scouring) and subsurface intakes (e.g. via weak acids). Periodic maintenance of filter bed for infiltration gallery if present (e.g. dredging, filter bed media replacement).	Visual inspection. Flow rate monitoring. Monitoring for polluting activities within exclusion zones (if in place).	Low to moderate, depending on configuration used and distance to desalination plant (but higher treatment costs compared to river and lake water intake).	No special requirements.

Table A2.2 Characteristics and application of common water treatment interventions (e.g. central water treatment at a water treatment plant)

Intervention	Target contaminants and treatment considerations	Key benefits	Key limitations	Construction/purchasing	Operations and maintenance	Monitoring ³²	Cost	Water characteristics typical for application
Roughing filtration (T.1.1)	Removal of particles.	Pre-treatment process that improves physical quality of source waters. Simple operation, usually no mechanical equipment. Improves efficacy of downstream treatment processes if present, including disinfection. Can be applied in resource constrained settings. Typically does not require treatment chemicals.	As roughing filtration is based on size exclusion, protozoa/helminth reduction will be similar to turbidity reduction, bacterial reduction is typically limited, and virus reduction expected to be minimal. No removal of organics or inorganics. Lacks residual disinfection capacity. May be prone to filter compaction and clogging – filter backwashing capacity required.	Expert knowledge or technical assistance needed for design or sizing. Basic construction. Materials and media typically locally available.	Operation and maintenance includes cleaning and backwashing the filter, valve maintenance, removal of floating/settled material. Periodic media replacement is required.	Flow rate. Visual inspection of product water. Product water turbidity monitoring.	Low to moderate.	Applicable to high turbidity waters.
Rapid sand filtration (T.1.2)	Removal of particles. Pathogen reduction can be enhanced by pre-filtration coagulation. Efficacy also dependent on filter media.	Moderate control of viruses, bacteria, protozoa/helminths if pre-filtration coagulation applied. Simple operation. Improves efficacy of downstream disinfection processes if present.	Limited reduction of viruses, bacteria, protozoa/helminths in the absence of pre-filtration coagulation. Efficacy of virus removal may vary (e.g. as a function of filter type and water quality). Limited organics or inorganics removal in the absence of pre-treatment. Lacks residual disinfection capacity. Requires backwashing capacity. Efficacy reduced during the period after backwashing (i.e. filter ripening period).	Expert knowledge required for design. Construction is simple. Materials and media typically locally available.	Regular operation and maintenance required, including backwashing, valve maintenance. Periodic media replacement is required.	Flow rate. Pressure (head loss). Visual inspection of filter bed (including media loss during backwash) and product water. Product water turbidity monitoring.	Low to moderate.	Applicable to variable turbidity waters.

³² Unless otherwise stated, monitoring in this context refers to routine operational monitoring to ensure interventions (or “control measure”) continue to operate within acceptable limits (refer to X.9 Water quality monitoring). In addition to the monitoring activities listed, periodic sanitary inspection and water quality monitoring should also be performed where applicable. For more information, see *Guidelines for drinking-water quality: small water supplies*. Geneva, World Health Organization; 2024.

Intervention	Target contaminants and treatment considerations	Key benefits	Key limitations	Construction/purchasing	Operations and maintenance	Monitoring ³²	Cost	Water characteristics typical for application
Microfiltration (T.1.3) Pore size: 0.1–10 µm	Removal of small particles. Broad spectrum control of bacteria and protozoa. Limited virus control.	Effective removal of bacteria, protozoa/helminths, suspended particles and colloids. Largely automated process. Typically requires less land (footprint) relative to conventional filtration systems.	Less effective for virus removal relative to other membrane types. Lacks residual disinfection capacity. Typically needs reliable power supply for continuous operation to ensure membrane performance. Requires periodic backflushing, and may require chemical treatment and/or pre-treatment. Membrane prone to fouling and requiring replacement. Requires adequate disposal of rejected waste stream.	Expert knowledge required for design. Pre-fabricated membranes are typically available. Basic to more complex installation. Consumables distribution chain required for cleaning chemicals.	Regular membrane and system maintenance, requiring skilled personnel or technical support.	Flow rate. System pressure. Visual inspection of product water. Influent and product water turbidity monitoring.	Moderate to high capital and operating and maintenance costs.	Applicable to low to moderate turbidity, or pre-treated, waters. Requires the absence of hard/sharp particles (which could damage the membrane), and the absence of high levels of organic matter, minerals and bacteria (which can lead to membrane fouling).
Coagulation/flocculation/sedimentation (T.1.4)	Removal of dissolved organic matter, (including taste and odour compounds), metals, particles. Moderate micro-organism control.	Reduces organic matter and turbidity. Removes suspended and dissolved contaminants (including colloids and algal cells). Improves efficacy of downstream filtration and disinfection if present.	Effectiveness, including removal of microorganisms, varies depending on influent water quality and coagulation conditions. Requires continuous supply of coagulant (usually widely available) and power for mixing. Discolouration and sediment deposit can occur when coagulant control is poor or under variable water quality conditions. Requires careful process control and monitoring (including optimization of flow rate, pH and coagulant dose). Lacks residual disinfection capacity. Requires long residence time. Requires large footprint relative to membrane filtration and coagulation/flocculation/rapid filtration. May result in residual coagulant in product water. Requires sludge removal/disposal.	Expert knowledge required for design. Specialized construction; materials typically locally available. Long life-span.	Specialized operation and maintenance required. Process control, including coagulant residence time optimization, coagulant dosing (e.g. jar testing). Sludge removal.	Flow rate (residence times). pH. Visual inspection of all process components (including floc formation). Product water turbidity monitoring.	Low (but influenced by operating costs).	Applicable to moderate to high turbidity waters.

Intervention	Target contaminants and treatment considerations	Key benefits	Key limitations	Construction/purchasing	Operations and maintenance	Monitoring ³²	Cost	Water characteristics typical for application
Coagulation/flocculation/filtration (also called direct filtration; T.1.5)	Broad spectrum control of micro-organisms. Removal of dissolved organic matter, (including taste and odour compounds), metals, particles.	Reduces organic matter and turbidity. Removes suspended and dissolved contaminants (including colloids and algal cells). Effective barrier for micro-organisms. Improves efficacy of downstream disinfection if present.	Effectiveness varies depending on influent water quality, filter media and coagulation conditions. Requires continuous supply of coagulant (usually widely available) and power for mixing. Requires careful process control and monitoring (including optimization of flow rate, pH and coagulant dose). Lacks residual disinfection capacity. Requires backwashing capacity (e.g. infrastructure, clean wash water source, wash water disposal, sludge disposal). Efficacy is reduced during the period after backwashing (i.e. filter ripening period).	Expert knowledge required for design. Specialized construction. Consumables supply chain required.	Specialized operation and maintenance required (as per row T.1.4 Coagulation/flocculation/sedimentation). Regular filter operation and maintenance required (as per row T.1.2 Rapid sand filtration).	As per rows T.1.2 Rapid sand filtration and T.1.4 Coagulation/flocculation/sedimentation.	Low (but influenced by operating costs).	Applicable to lower turbidity waters.
Chlorination (T.2.1) ³³	Control of viruses and bacteria. Ineffective control of some protozoa, in particular <i>Cryptosporidium</i> oocysts. Removal of certain organics.	Can effectively inactivate bacteria, viruses and some protozoa (although not effective against <i>Cryptosporidium</i> oocysts). Can support removal of some chemicals (e.g. oxidizes reduced inorganics to form insoluble products for removal by subsequent filtration). Provides some residual protection against low-level microbial recontamination and growth. Can be dosed by pumping or by gravity.	Ineffective against <i>Cryptosporidium</i> oocysts. Efficacy is sensitive to factors that include pH, temperature, turbidity, contact time, and chlorine demand. ³⁴ Can form disinfection by-products, particularly when organic matter is not adequately removed from the water before disinfection. ³⁵ Requires careful operation and monitoring to ensure optimal disinfection. Need to monitor/adjust dosing to meet variable chlorine demand in the water. Users may object to taste and odour. Chlorine can degrade over time if stored inappropriately (e.g. in direct sunlight).	Simple construction of dosing equipment. Chlorine supply chain required, although readily available in various forms (e.g. liquid, powder, tablet).	Skilled operators required (although relatively easy to use compared to other treatment technologies including other disinfectants). Frequent operational control required (e.g. dose optimization). Requires good storage/stock management practices.	Frequent free chlorine residual dose monitoring. Frequent pH, turbidity and contact time monitoring. Routine equipment inspection/replacement due to corrosion potential.	Low (but influenced by operating costs).	Ideally applied to low turbidity, low organic waters.

³³ Other forms of chlorine include chlorine dioxide and chloramine. For information, see *Water treatment and pathogen control: process efficiency in achieving safe drinking-water*. Geneva, World Health Organization; 2004.

³⁴ Organic and inorganic material exerts a chlorine demand, limiting the concentration of free chlorine available for disinfection.

³⁵ Chlorine can react with organic material in water to form potentially hazardous disinfection by-products. Thus, precursor organic matter should be removed from water before disinfection where feasible. However, where disinfection by-products are formed, the health risks from these by-products at the levels at which they occur in drinking-water are small in comparison with the risks associated with inadequate disinfection. As such, disinfection should not be compromised in an attempt to control such by-products.

Intervention	Target contaminants and treatment considerations	Key benefits	Key limitations	Construction/purchasing	Operations and maintenance	Monitoring ³²	Cost	Water characteristics typical for application
On-site electro-chlorination (T.2.2)	See row T.2.1 <i>Chlorination</i> . Also compared to chlorination, reduces need for transport, handling and storage of large quantities/volumes of chlorine. Less labour intensive than the application of solid or liquid hypochlorite.	See row T.2.1 <i>Chlorination</i> . Also compared to chlorination, reduces need for transport, handling and storage of large quantities/volumes of chlorine. Less labour intensive than the application of solid or liquid hypochlorite.	See row T.2.1 <i>Chlorination</i> as applicable. Requires higher quality water than standard chlorination to avoid electrode fouling. The feed water for the electro-chlorination unit may require pre-treatment (e.g. water softening). Requires reliable power supply when operational.	Expert knowledge required for design and construction. Adequate footprint required for brine storage tanks. Once installed, the process is not easily scaled-up. Requires supply of salt.	Skilled operators required. Routine cleaning of electrodes.	Operating voltage rate, current, ratio of salt usage to operating time. Water hardness. Hypochlorite concentration. Brine concentration. See also row T.2.1 <i>Chlorination</i> .	Moderate.	Requires feed water that is soft with low metals (e.g. low iron, manganese, lead).
Ultraviolet (UV) light disinfection (T.2.3)	Broad spectrum control of micro-organisms. Limited adenovirus control at low UV doses.	Effective barrier for most viruses, bacteria and protozoa/helminths (depending on UV dose applied). No-chemicals needed. Generates photo-oxidants which may accelerate organic contaminant degradation. Less potential to form disinfection by-products. Does not alter the taste and odour of the water.	Requires low turbidity and low colour (i.e. high UV transmittance) water for effectiveness – pre-treatment may be needed. Lacks residual disinfection capacity. Requires reliable power supply when operational. Some lamps require a warm-up period when first turned on, during which there is reduced efficacy.	Expert knowledge required for design. Pre-fabricated, factory validated UV units are available. Basic to more complex installation. Requires supply chain (e.g. for replacement tubes, lamps). Requires reliable power source.	Simple operation and maintenance, including cleaning of UV tubes to prevent sediment build-up. Replacement of UV source at end of lifetime.	UV transmittance of influent water. Flow rate/contact time. UV dose. Lamp status indicator (if present). Lamp run-time (to determine end of life). Cleanliness of tubes.	Low to moderate (reflecting higher capital costs than other disinfection approaches e.g. chlorination).	Applicable to low turbidity and low colour waters (i.e. high UV transmittance), with minimal levels of metals, dissolved salts.
Slow sand filtration (T.2.4)	Broad spectrum control of micro-organisms. Removal of particles (efficiency may vary).	Effective barrier for micro-organisms. Simple operation. No chemicals needed. Control of biodegradable organic contaminants. Can be operated by gravity or by pumping.	May require pre-treatment. Operation depends on development of biological layer (requires ripening time). Effectiveness influenced also by grain size, pH, temperature. Requires slow flow rate. Variable particle removal. Lacks residual disinfection capacity. Top of the filter bed requires routine scraping to avoid clogging (requires safe sludge disposal). Efficacy may decrease at lower temperatures. Vulnerable to shock chemical loads in the influent water.	Expert knowledge required for design. May require large footprint. Specialized construction. Construction can use locally-available materials. Typically long life-span. May require pre-treatment with T.1.1 <i>Roughing filter</i> if source water turbidity is high.	Simple operation and maintenance but regular maintenance required, including for backwashing, filter media washing and filter ripening.	Visual inspection. Flow rate.	Low.	Applicable to low turbidity waters.

Intervention	Target contaminants and treatment considerations	Key benefits	Key limitations	Construction/purchasing	Operations and maintenance	Monitoring ³²	Cost	Water characteristics typical for application
Ultrafiltration (T.2.5) Pore size: 0.005–0.1 µm	Broad spectrum control of microorganisms. Removal of small particles.	Effective barrier for bacteria, protozoa/helminths, suspended particles and colloids. Effective for viruses at smaller pore sizes. Largely automated process. Modular system, requires a small footprint.	Requires high-quality, pre-treated waters. Prone to membrane fouling, requires membrane replacement. Lacks residual disinfection capacity. Requires constant pumping and energy for operation. Requires adequate disposal of rejected waste stream.	Expert knowledge required for design. Pre-fabricated membranes are available. Basic to more complex installation. Consumables distribution chain required for cleaning chemicals, membrane replacement.	Regular membrane system maintenance, including backwashing, and chemical cleaning.	Flow rate. System pressure. Influent and product water turbidity.	Moderate to high capital and operating costs.	Applicable to low to moderate turbidity waters. Requires the absence of hard/sharp particles, as well as the absence of high levels of organic matter and bacteria.
Pasteurization (T.2.6)	Broad spectrum control of microorganisms.	Effective barrier for microorganisms. Can use multiple heat sources. Easy to operate and maintain. No chemicals needed. No disinfection by-product formation.	May require pre-treatment. Does not remove particles, turbidity, chemicals, colour. Lacks residual disinfection capacity. Burn risk to users from hot surfaces. Water requires cooling before consumption.	Expert knowledge required for design. Basic to more complex installation.	Regular cleaning of reflecting surfaces. Thermostatic valve operation and maintenance.	Temperature. Flow rate. Influent turbidity.	Low to moderate installation costs depending on scale and operational costs.	Applicable to low turbidity waters and waters with low levels of chemical contaminants and colour.
Fluoride removal methods (T.3.1) ³⁶	Removal of fluoride.	Precipitation/coagulation: <i>Nalgonda technology:</i> Uses materials that are typically locally-available and low cost. Adsorption and ion-exchange: <i>Activated alumina:</i> High fluoride uptake capacity. Filter media can be regenerated (i.e. reused). <i>Bone char:</i> Uses materials that are typically locally-available and low cost. Requires short contact time between the media and water for effective fluoride removal.	Precipitation/coagulation: <i>Nalgonda technology:</i> Labour-intensive process. Fluoride adsorption capacity is more limited. Produces waste that must be adequately disposed. Adsorption and ion-exchange: <i>Activated alumina:</i> Requires skilled operators (including for media regeneration). Requires costly media. <i>Bone char:</i> Low to moderate fluoride uptake – requires regular media replacement. Requires costly infrastructure for media manufacture (e.g. kiln). Media may be of variable quality.	Expert knowledge required for design. Basic construction. Reliable power supply may be required. Needs supply chain for chemicals.	Typically requires skilled operators. Chemical addition required for precipitation/coagulation. Regular sludge removal/disposal. Media replacement for Nalgonda technology and bone char. Media regeneration for activated alumina.	Flow rate. Influent and product water fluoride concentration (i.e. for contaminant breakthrough).	Low to moderate depending on the technology applied.	Applicable to stable pH or low turbidity waters depending on the technology applied.

36 For removal of this contaminant by membrane technologies, see rows T.5.1 Membrane distillation and T.5.2 Reverse osmosis. These technologies can remove other contaminants during treatment (e.g. pathogens, chemicals), but can be more costly and complex to operate.

Intervention	Target contaminants and treatment considerations	Key benefits	Key limitations	Construction/purchasing	Operations and maintenance	Monitoring ³²	Cost	Water characteristics typical for application
Arsenic removal methods (T.3.2) ³⁶	Removal of arsenic.	<i>Precipitation/coagulation:</i> Low cost. Uses materials that are typically locally available. <i>Iron-based solids:</i> Effective removal of pentavalent arsenic, with acceptable removal of trivalent arsenic. Commercially available in many settings. <i>Adsorption and ion-exchange:</i> <i>Activated alumina and ion exchange resins:</i> High arsenic uptake capacity. Commercially available in many settings.	<i>Precipitation/coagulation:</i> Labour-intensive process. Requires pre-oxidation. Produces arsenic-rich waste that must be adequately disposed. <i>Iron-based solids:</i> Produces arsenic-rich waste that must be adequately disposed. <i>Adsorption and ion-exchange:</i> <i>Activated alumina:</i> Requires skilled operators (including for media regeneration). <i>Ion exchange resins:</i> May experience interference from sulfates, phosphates, and total dissolved solids (i.e. competing ions).	Expert knowledge required for design. Basic construction. Reliable power supply may be required. Needs supply chain for chemicals.	Typically requires skilled operators. Chemical addition required for precipitation/coagulation. Regular sludge removal/disposal. Media regeneration for activated alumina and ion exchange.	Flow rate. Influent and product water arsenic concentration (i.e. for contaminant breakthrough).	Low to moderate depending on the technology applied.	Applicable to stable pH or low turbidity waters depending on the technology applied. For ion exchange resins, requires waters low in potentially competing ions. ³⁷
Activated carbon (T.4.1)	Removal of organic contaminants.	Simple operation. Good organics removal, as well as removal of taste and odour compounds. Some particle removal. Some limited bacteria and protozoa/helminth removal. Can be applied in granular form as a filter or in powdered form as a slurry to coagulation/ sedimentation unit. Powdered form can be used for episodic events, e.g., chemical spills, taste and odour events.	Requires pre-treatment Bacterial growth may occur on media. Natural organic matter competes with organics removal. Need to reactivate media for effective organics removal.	Expert knowledge required for design. Basic construction. Media typically locally available.	Requires regular media replacement or reactivation.	Flow rate. System pressure. Contaminant breakthrough. Ultraviolet light absorption or total organic carbon breakthrough as a surrogate for contaminants of concern.	Moderate to high (influenced by media replacement).	Applicable to soft water, with low turbidity, low organics and with high microbial quality

³⁷ Competing ions can displace pentavalent arsenic, leading to the uncontrolled release of large quantities of arsenic into the treated water.

Intervention	Target contaminants and treatment considerations	Key benefits	Key limitations	Construction/ purchasing	Operations and maintenance	Monitoring ³²	Cost	Water characteristics typical for application
Ozonation (T.4.2)	Broad spectrum control of microorganisms. Eliminates a variety of inorganic and organic contaminants.	Effectively inactivates bacteria and viruses. Protozoa inactivation requires higher doses. Strong oxidant with a high disinfectant capacity. Short reaction time. Removes colour taste, and odour. Oxidizes, iron and manganese chemicals (i.e. to form insoluble products for removal by subsequent filtration). Good removal of algae, most inorganic matter and some organic matter and organic contaminants. Can enhance coagulation processes. Effective over a broad pH range. No chemical residuals. Low potential for disinfection by-product formation if bromide not present.	Poor inactivation of some protozoa. Efficacy is temperature dependent. Toxic, flammable, unstable gas. May produce undesirable by-products such as aldehydes and ketones, and bromate if bromide is present. Lacks residual disinfection capacity. Special mixing devices are required. Does not oxidize some organics efficiently. Requires reliable power supply.	Expert knowledge required for design. Specialized construction for onsite generation. Requires appropriate site security and safety measures.	Complex. Skilled staff required for routine operation and maintenance, and/or access to specialized maintenance support.	Ozone preparation and monitoring. Cleaning and drying of feed gases. Monitoring of ozone off-gas.	High.	Applicable to waters low in hardness, and with low bromide concentrations.
Nanofiltration (T.4.3) Pore size: 0.001–0.01 µm	Broad spectrum control of microorganisms. Removal of hardness, large organic molecules, inorganic pollutants, small particles.	Effective barrier for bacteria, protozoa, suspended particles and colloids. Can be effective for viruses depending on the filter pore size, membrane layer and material. Reduces hardness, colour, odour, inorganic pollutants, heavy metals, and endotoxins. Largely automated process. May desalinate brackish waters.	Requires high-quality, pre-treated waters. Membrane prone to fouling/ replacement. Relatively high energy demand. The product water can be corrosive. Requires adequate disposal of rejected waste stream.	Expert knowledge required for design. Pre-fabricated membranes are available. Relatively complex and expensive installation. Needs supply chain for cleaning chemicals.	Regular, specialized operation and maintenance required with access to specialized maintenance support.	Flow rate. System pressure. Visual inspection of product water. Influent and product water turbidity. Pre-treatment and post-treatment efficiencies.	High.	Applicable to low turbidity waters. Requires the absence of hard/ sharp particles, as well the absence of high levels of organic matter and bacteria.

Intervention	Target contaminants and treatment considerations	Key benefits	Key limitations	Construction/purchasing	Operations and maintenance	Monitoring ³²	Cost	Water characteristics typical for application
Membrane distillation (T.5.1)	Broad spectrum control of micro-organisms. Removal of dissolved or suspended contaminants, including minerals, salts, organic compounds.	Effective barrier for micro-organisms. Needs minimal pre-treatment; suitable for high salinity waters. Low energy inputs required. Easily scalable.	Requires a constant source of heat. Potential for scaling and fouling of membranes from inorganic deposits. Requires adequate disposal of rejected waste stream.	Expert knowledge required for design. Pre-fabricated membranes are available. Relatively complex and expensive installation. Needs supply chain for cleaning chemicals.	Regular, specialized operation and maintenance required.	Flow rate. System pressure. Temperature. pH. Flux rate. Visual inspection of product water. Influent and product water turbidity.	High capital and relatively lower operating costs.	Requires the absence of hard/sharp particles, as well as the absence of high levels of organic matter and bacteria.
Reverse osmosis (T.5.2) (included also in T.3.1 Fluoride removal methods and T.3.2 Arsenic removal methods)	Broad spectrum control of micro-organisms. Removal of hardness, organics, small particles.	Effective barrier for micro-organisms. Effective barrier to most chemicals including fluoride, arsenic, manganese, nitrate, hardness, colour, odour, inorganic pollutants, heavy metals (including lead) and endotoxins. Suitable for high salinity waters. Largely automated process.	Incomplete removal of smaller elements such as boron. May experience membrane fouling, requiring replacement. Requires relatively high energy/pressure, reliable power supply. Typically requires pre-treatment of influent water (e.g. by T.2.5 Ultrafiltration). Requires adequate disposal of rejected waste stream.	Expert knowledge required for design. Pre-fabricated membranes are available. Complex and relatively expensive installation. Needs supply chain for cleaning chemicals.	Regular, specialized operations and maintenance required.	Flow rate. System pressure. Visual inspection of product water. Influent and product water conductivity and turbidity. Pre-treatment and post-treatment efficiencies.	High.	Applicable to low turbidity waters. Requires absence of hard and sharp particles. ³⁸ Requires low levels of organic matter and bacteria.

³⁸ Reverse osmosis membranes are also sensitive to operating parameters such as feed water temperature, pressure and pH.

Table A2.3 Characteristics and application of common household water treatment interventions³⁹

Intervention	Aim, target contaminants, treatment considerations	Key benefits	Key limitations	Key factors affecting performance	Operations and maintenance	Monitoring ⁴⁰	Cost	Typical application
Storage tanks or reservoirs (H.1)	Protection against contamination during storage. Ensuring adequate water quantity, most appropriate where optimal access to water supply (e.g. water supplied on premises and continuously available) is not guaranteed.	Reduces contamination risks where safe storage is practiced. Reduces risk of vector breeding for vectors that rely on open water provided hatches are sealed and outlets of any overflows are protected by mosquito proof screens. Versatile, broadly accepted approach. Easily scalable. Uses locally available materials.	Storage tanks prone to contamination if not appropriately designed or maintained. Larger tanks require a larger footprint.	Presence of a tightly fitting lid. Cleanliness, including the absence of hard to clean areas (e.g. hollow handles).	Routine maintenance and cleaning / disinfection. Larger tanks require periodic sediment removal and disinfection. Sediment needs to be disposed of appropriately.	Visual inspection of water. Condition and cleanliness of container/tank. Integrity of container/tank and ancillary components (e.g. tap, lid, cover, roof, walls, air vents, overflow pipe).	Low to moderate depending on scale. Higher costs relative to open containers.	Storage of clean potable water.
Ceramic filtration (H.2)	Removal of parasites, protozoa, and some bacteria.	Low risk of recontamination where there is an integrated storage container. No chemical addition required (unless material embedded within the filter). Simple to use, no power requirements. May be locally produced/available. Widely accepted, improves appearance of water, with minimal change in taste.	Typically not effective against enteric viruses, chemicals, heavy metals. For high turbidity waters, pre-treatment may be required (e.g. settling). Lacks residual disinfection capacity. Flow rate is low (1–2 L/hour; slower in turbid waters). Variability in quality of locally produced filters (influenced also by pore size). Needs regular cleaning, and filter needs periodic replacement or recoating. Breaks easily (difficult to store and transport).	Influent water quality (including turbidity). Flow rate. Media and pore size. Manufacturing quality.	Routine inspection (e.g. for cracks) and cleaning of filter (scrubbing with soft brush and clean water only). Basic user training recommended.	Visual inspection of product water. Condition and cleanliness of the filter and ancillary equipment.	Low.	Ideally applied to low turbidity waters with low levels of viruses. Most appropriate where: – pathogen of concern is known (e.g. <i>Cryptosporidium</i>), given limited virus removal – there is capacity and proven quality filter production.

³⁹ In addition to the interventions presented, the household should always ensure hygienic storage and handling to minimize the risk of recontamination after household-level treatment. This includes safe sanitation and adequate hygiene practices. Effective handwashing is particularly important before handling drinking-water, or coming into contact with the household treatment unit, storage containers, and associated utensils.

⁴⁰ Unless otherwise stated, monitoring in this context refers to operational monitoring to ensure interventions (or “control measure”) continue to operate within acceptable limits (refer to X.9 Water quality monitoring). In addition to the monitoring activities listed, periodic sanitary inspection and water quality monitoring should also be performed where applicable. For more information, see *Guidelines for drinking-water quality: small water supplies*. Geneva, World Health Organization, 2024.

Intervention	Aim, target contaminants, treatment considerations	Key benefits	Key limitations	Key factors affecting performance	Operations and maintenance	Monitoring ⁴⁰	Cost	Typical application
Ultrafiltration (H.3)	Broad spectrum control of micro-organisms (dependent on pore size). Removal of particles.	Effective barrier for viruses, bacteria, protozoa/helminths, suspended particles and collioids. Low risk of recontamination where there is an integrated storage container. Simple to use. Improves appearance of water (enhances acceptability).	Larger pore sizes (e.g. > 0.04 µm) will be less effective/ineffective against viruses. Lacks residual disinfection capacity. Requires high-quality, pre-treated waters. Needs regular cleaning. Supply chain for spare parts needs to be available.	Membrane pore size. Integrity of the membrane and seals. Membrane cleanliness. Manufacturing quality.	Routine backflushing, cleaning (may involve use of chemicals). Routine cleaning/disinfection of ancillary equipment (e.g. taps, lid, storage container). Basic user training recommended.	Visual inspection of product water. Condition and cleanliness of ancillary equipment. If practical, flow rate and system pressure.	Moderate to high.	Ideally applied to low to medium turbidity waters. Requires the absence of hard/sharp particles, and also high levels of organic matter and bacteria. Most appropriate where: – removal of broad spectrum of pathogens required – funds are available to support initial filter costs for low-income users.
Chlorination (H.4)	Control of viruses and bacteria. Ineffective control of some protozoa, in particular <i>Cryptosporidium</i> oocysts. Removal of certain organics.	Can effectively inactivate bacteria and viruses and some protozoan inactivation (although not effective against <i>Cryptosporidium</i> oocysts). Provides some residual protection against low-level microbial recontamination and growth. Simple to use. Widely available, local production possible. Portable, easily packaged and easy to transport in emergencies.	Ineffective against several protozoa, including <i>Cryptosporidium</i> oocysts. Efficacy is sensitive to factors that include pH, temperature, turbidity, contact time, and chlorine demand. ⁴¹ Can form disinfection by-products, particularly when organic matter is not adequately removed from the water before disinfection (e.g. in turbid waters). ⁴² Requires careful operation and monitoring to ensure optimal disinfection. Need to monitor/adjust dosing to meet variable chlorine demand in the water. Users may object to taste and odour. Chlorine can degrade over time if stored inappropriately (e.g. in direct sunlight).	Influent water quality (including turbidity). Water quality characteristics (e.g. pH, temperature, organic content). Contact time. Free chlorine concentration.	Dosage optimization. Chlorine supply chain required. Basic user training recommended.	Chlorine dose and free chlorine residual. Ideally also pH, turbidity and contact time.	Low.	Ideally applied to low turbidity, low organic waters (e.g. pre-treatment may be required). Most appropriate where pathogen of concern is known (e.g. <i>Vibrio cholerae</i>) as chlorine does not provide protection against some protozoa.

⁴¹ Organic and inorganic material exerts a chlorine demand, limiting the concentration of free chlorine available for disinfection.

⁴² Chlorine can react with organic material in water to form potentially hazardous disinfection by-products. Thus, precursor organic matter should be removed from water before disinfection

where feasible. Including pre-treatment of turbid water. However, the health risks from these by-products at the levels at which they occur in drinking-water are small in comparison with the risks associated with inadequate disinfection. As such, disinfection should not be compromised in an attempt to control such by-products.

Intervention	Aim, target contaminants, treatment considerations	Key benefits	Key limitations	Key factors affecting performance	Operations and maintenance	Monitoring ⁴⁰	Cost	Typical application
Boiling (H.5)	Broad spectrum control of micro-organisms.	Effective against all pathogen classes. No chemical addition, or disinfection by-product formation. Can be powered by multiple sources (e.g. wood, biogas, electricity). Simple to use, wide cultural acceptance.	Does not remove turbidity, most chemical contaminants, organic matter, colour. Lacks residual disinfection capacity. Fuel requirement can be costly (including the opportunity cost for time taken to gather fuel if required). May impart a taste that affects user acceptability. Requires cooling time before consumption (if not used for hot drinks).	Achievement of a rolling boil.	Sourcing fuel. Cooling water.	Achievement of a rolling boil.	Moderate to high depending on fuel consumption/ availability.	Ideally applied to low turbidity waters, and waters with no/low levels of chemical contaminants.
Pasteurization (H.6)	Broad spectrum control of micro-organisms.	Effective against all pathogen classes. No chemical addition, or disinfection by-product formation. Low-cost, relatively easy to operate and maintain. Typically, locally available. Can use multiple heat sources.	Does not remove particles, turbidity, chemical contaminants, colour. Lacks residual disinfection capacity. Solar-powered systems affected by weather conditions. Risk of burn injuries from hot surfaces. Requires cooling time before consumption (if not used for hot drinks).	Temperature. Time. If solar powered, weather conditions.	Cleaning reflecting surfaces regularly. Thermostatic valve operation and maintenance required. Basic user training recommended.	Temperature. Time. Flow rate. Influent turbidity.	Low operational costs, low to moderate installation costs depending on scale.	Ideally applied to low turbidity waters, with low levels of chemical contaminants, colour. Pre-treatment may be required.
Biosand filtration (also called slow sand filtration; H.7)	Broad spectrum control of micro-organisms. Limited adenovirus control at low UV doses.	Effective barrier for most viruses, bacteria and protozoa (depending on the UV dose applied). Non-chemical approach. Less potential to form disinfection by-products. Does not alter the taste and odour of the water.	Requires reliable energy source. Requires high quality water (i.e. high UV transmittance) – pre-treatment may be needed. Colour and turbidity reduce effectiveness. Lacks residual disinfection capacity. Some lamps require a short warm-up period when first turned on, during which there is no/reduced efficacy.	Expert knowledge required for design. Prefabricated UV units are available. Basic to more complex installation. Requires supply chain (e.g. for replacement tubes, lamps). Requires reliable power source.	Simple maintenance, including cleaning of UV lamp tubes after sediment build-up. Replacement of UV lamps, tubes. Consumables supply chain required (e.g. lamps, tubes). Basic user training recommended.	Visual inspection of influent water (i.e. cloudiness). Flow rate/contact time. UV transmittance of influent water. UV dose. Lamp status indicator/alarm if available. Lamp age/run time (to approximate end of life). Cleanliness of tubes.	Moderate.	Ideally applied to low turbidity waters, with minimal levels of metals, dissolved salts. Pre-treatment may be required (e.g. via filtration, sedimentation or activated carbon).

Intervention	Aim, target contaminants, treatment considerations	Key benefits	Key limitations	Key factors affecting performance	Operations and maintenance	Monitoring ⁴⁰	Cost	Typical application
Ultraviolet (UV) light disinfection (H.8)	Broad spectrum control of micro-organisms. Limited adenovirus control at low UV doses.	Effective barrier for most viruses, bacteria and protozoa (depending on the UV dose applied). Non-chemical approach. Less potential to form disinfection by-products. Does not alter the taste and odour of the water.	Requires reliable energy source. Requires high quality water (i.e. high UV transmittance) – pre-treatment may be needed. Colour and turbidity reduce effectiveness. Lacks residual disinfection capacity. Some lamps require a short warm-up period when first turned on, during which there is no/reduced efficacy.	Expert knowledge required for design. Prefabricated UV units are available. Basic to more complex installation. Requires supply chain (e.g. for replacement tubes, lamps). Requires reliable power source.	Simple maintenance, including cleaning of UV lamp tubes after sediment build-up. Replacement of UV lamps, tubes. Consumables supply chain required (e.g. lamps, tubes). Basic user training recommended.	Visual inspection of influent water (i.e. cloudiness). Flow rate/contact time. UV transmittance of influent water. UV dose. Lamp status indicator/alarm if available. Lamp age/run time (to approximate end of life). Cleanliness of tubes.	Moderate.	Ideally applied to low turbidity waters, with minimal levels of metals, dissolved salts. Pre-treatment may be required (e.g. via filtration, sedimentation or activated carbon).
Solar water disinfection (H.9)	Control for bacteria and protozoa; control of some viruses. Level of microbial control depends on temperature and exposure time.	Minimal likelihood of recontamination when retained in disinfecting container. Requires low/no maintenance. Minimal change in taste. Simple to use. Requires no power.	Needs pre-treatment of turbid waters. Treatment time is relatively long and varies with sun intensity (approx. 6 hours under 50% cloudy sky). May not have a visual indicator to signal treatment complete. Treatment capacity depends on availability of clean, intact containers. Containers must be placed where exposed to sun and not disturbed (e.g. on a roof).	Cleanliness, type and condition of containers. Influent water quality (turbidity). Sun intensity (weather, geographic location). Degree of disturbance during treatment.	Cleaning or replacement of containers. Planning of anticipated water needs. Basic user training recommended.	Weather conditions. Exposure time.	Low.	Ideally applied to low turbidity waters where there is sufficient solar radiation (e.g. between 35°N and 35°S latitude).

Intervention	Aim, target contaminants, treatment considerations	Key benefits	Key limitations	Key factors affecting performance	Operations and maintenance	Monitoring ⁴⁰	Cost	Typical application
Fluoride removal filters (H.10)	Removal of fluoride.	<i>Precipitation/coagulation:</i> Nalgonda technology: Uses readily available chemicals. <i>Adsorption and ion-exchange:</i> Activated alumina: Simple to use. High fluoride removal capacity. Some filter materials can be regenerated and reused by trained individuals. <i>Bone char:</i> Simple to use. Lower cost. Some filter materials can be regenerated (typically off-site by trained individuals) and reused.	<i>Precipitation/coagulation:</i> Nalgonda technology: Can be complicated and prone to error for household use. Produces sludge that must be removed and safely disposed. Only moderate fluoride removal. <i>Adsorption and ion-exchange:</i> Activated alumina: Filter media may not be available locally, be expensive and of variable quality. Requires chemicals for media regeneration. <i>Bone char:</i> More limited fluoride removal capacity. Requires chemicals for media regeneration.	Fluoride raw water concentration. Flow rate. Filter uptake capacity.	Regular addition of chemicals, maintenance, including sludge removal and disposal for Nalgonda technology. For activated alumina and bone char, media regeneration required (typically provided by a trained third party e.g. filter distributor). Basic user training recommended in all cases.	Precipitate addition for Nalgonda technology. Approximate filter saturation point for activated alumina and bone char.	Low for Nalgonda technology. Moderate to high for activated alumina. Low to moderate for bone char.	Applicable to stable pH or low turbidity waters depending on the technology applied.
Arsenic removal filters (H.11)	Removal of arsenic.	Low-cost, simple to operate. Uses locally available material and chemicals.	Arsenic removal efficiency varies. Not suitable for anion-rich waters (e.g. sulphate and phosphate are competing ions).	Arsenic raw water concentration. Flow rate. Filter contact time. Filter uptake capacity.	Periodic cleaning, flushing. Filter replacement. Basic user training recommended.	Approximate filter saturation point.	Low.	Applicable to stable pH or low turbidity waters depending on the technology applied. For ion exchange resins, requires waters low in potentially competing ions. ⁴³

⁴³ Competing ions can displace pentavalent arsenic, leading to the uncontrolled release of large quantities of arsenic into the treated water.

World Health Organization
20 Avenue Appia
1211 Geneva 27
Switzerland

gdwq@who.int
<https://www.who.int/health-topics/water-sanitation-and-hygiene-wash>