Compendium of Drinking-water Systems and Technologies from Source to Consumer

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from Source to Consumer

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The World Health Organization's (WHO) Guidelines for drinking-water quality recommend the implementation of a "Framework for safe drinking-water" as the basic and essential requirement to ensure the safety of drinking-water (WHO, 2017). This framework comprises health-based targets (established by a competent health authority), adequate and properly managed drinking-water systems to achieve the health-based targets, and independent surveillance.

Effective water supply systems require the provision of adequate infrastructure, and effective planning and management, which can be achieved through water safety planning - a comprehensive risk assessment and management approach encompassing all steps in a water supply system, whose principles should be applied by all water suppliers to ensure drinking-water safety (WHO, 2017). In addition to drinking-water quality considerations, there is a need to ensure there are sufficient quantities of water for household use (including for drinking, food preparation and hygiene) to protect public health and for well-being and prosperity (WHO, 2017; WHO 2020).

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

The compendium brings together a concise overview of drinking water systems and technologies with a focus on low- and middle-income countries. 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.

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.

The compendium 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 vs. point-of use and rural vs. peri-urban or urban contexts.

Structure of the compendium

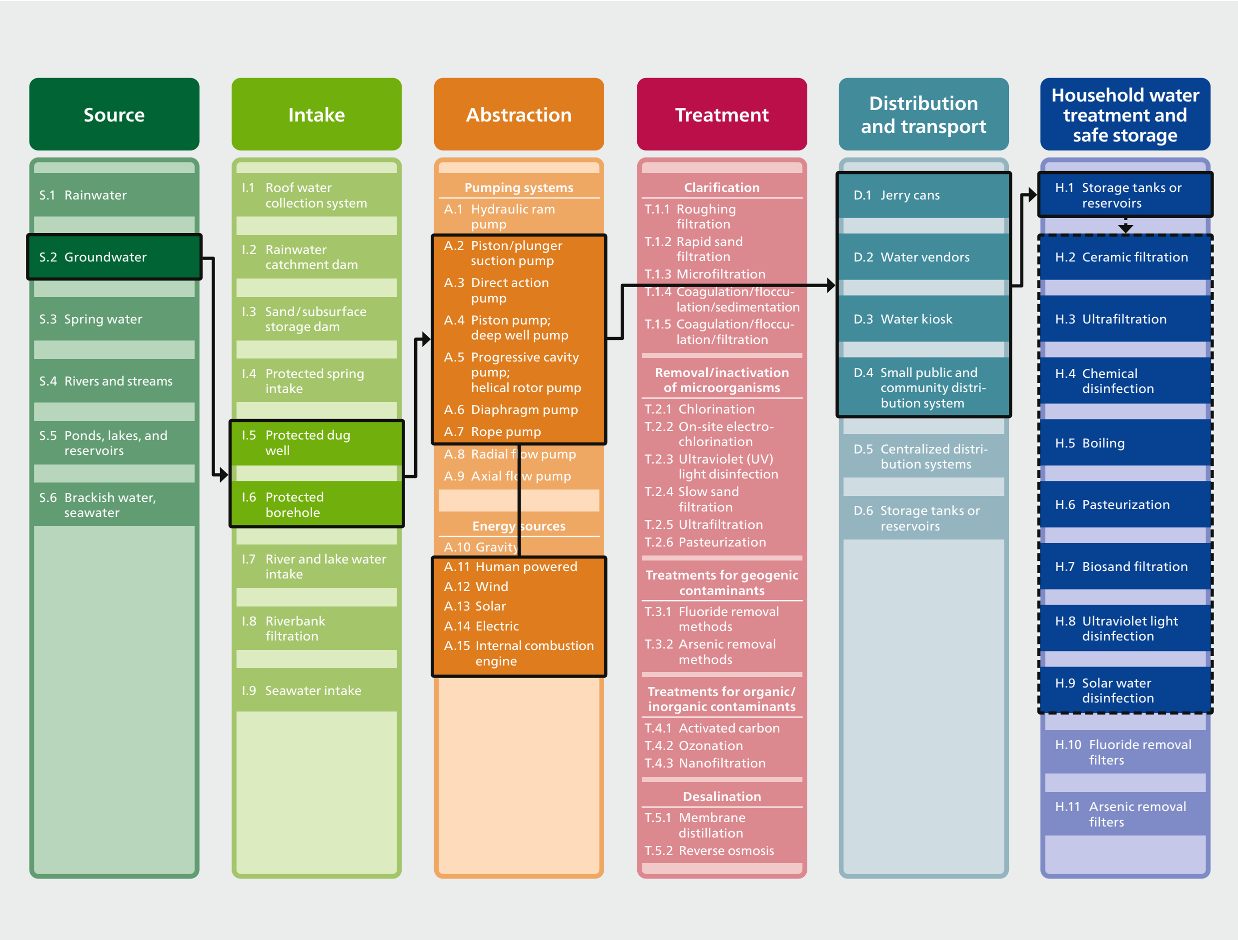
The compendium describes nine typical drinking water supply schemes with differing water sources and water qualities (Part 1: System templates). The system descriptions provide information about all technological steps from water sources and water withdrawal technologies to household water treatment and storage. Therefore, the water supply systems are disaggregated in their main components, namely:

- S. Sources: all water sources
- I. Intakes: 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
- U. User safety: 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.

In addition to technology selection, implementing an effective and sustainable water supply system depends also on factors and local considerations such as planning, management, monitoring, and the availability of appropriate external supports. The third part of this document (Part 3: Cross-cutting issues) introduces topics relevant for the effective longer-term management of water supply systems. This includes risk management strategies, post-construction support, and gender issues.

Part 1 | System templates



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. Color-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. 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

Source

- 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

Intake

- 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

Abstraction

Pumping systems

- 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

Energy sources

- A.10 Gravity
- A.11 Human powered
- A.12 Wind
- A.13 Solar
- A.14 Electric
- A.15 Internal combustion engine

Treatment

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

Removal/inactivation of microorganisms

- T.2.1 Chlorination
- T.2.2 On-site electro-chlorination
- T.2.3 Ultraviolet (UV) light disinfection
- T.2.4 Slow sand filtration
- T.2.5 Ultrafiltration
- T.2.6 Pasteurization

Treatments for geogenic contaminants

- T.3.1 Fluoride removal methods
- T.3.2 Arsenic removal methods

Treatments for organic/inorganic contaminants

- T.4.1 Activated carbon
- T.4.2 Ozonation
- T.4.3 Nanofiltration

Desalination

- T.5.1 Membrane distillation
- T.5.2 Reverse osmosis

Distribution and transport

- D.1 Jerry cans
- D.2 Water vendors
- D.3 Water kiosk
- D.4 Small public and community distribution system
- D.5 Centralized distribution systems
- D.6 Storage tanks or reservoirs

Household water treatment and safe storage

- 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 light disinfection
- H.9 Solar water disinfection
- H.10 Fluoride removal filters
- H.11 Arsenic removal filters

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 or collected. 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. 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:

Supply (L/year) = Rainfall (mm/year) × Roof area (m^2) × 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 spilling, evaporation, wind, overflowing gutters, leaky collection pipes, and first-flush devices.

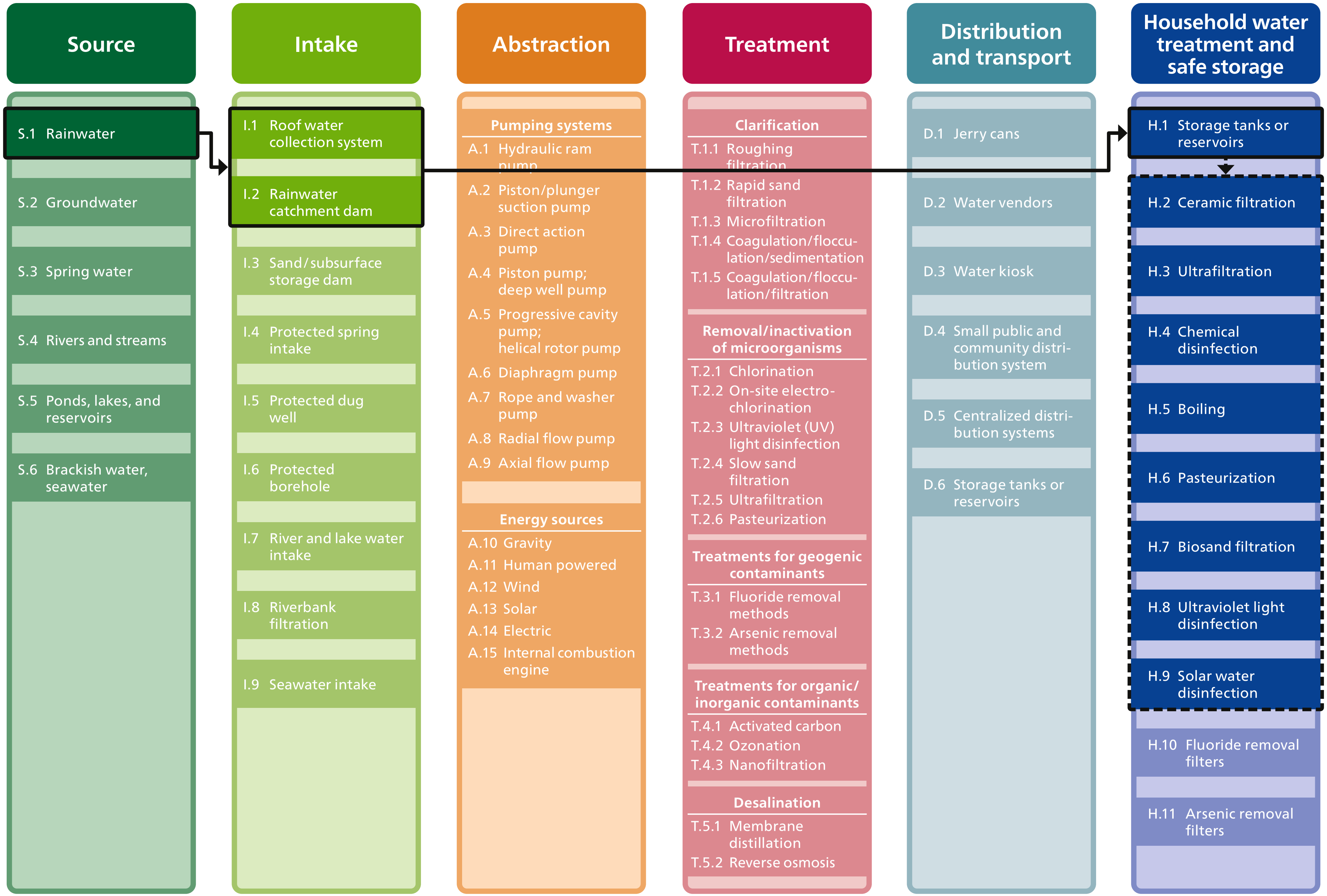
Considerations

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. Rain water 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 color of the water. Bamboo or straw roofs are least suitable for rainwater collection because 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, 2021). 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 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;
- 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.

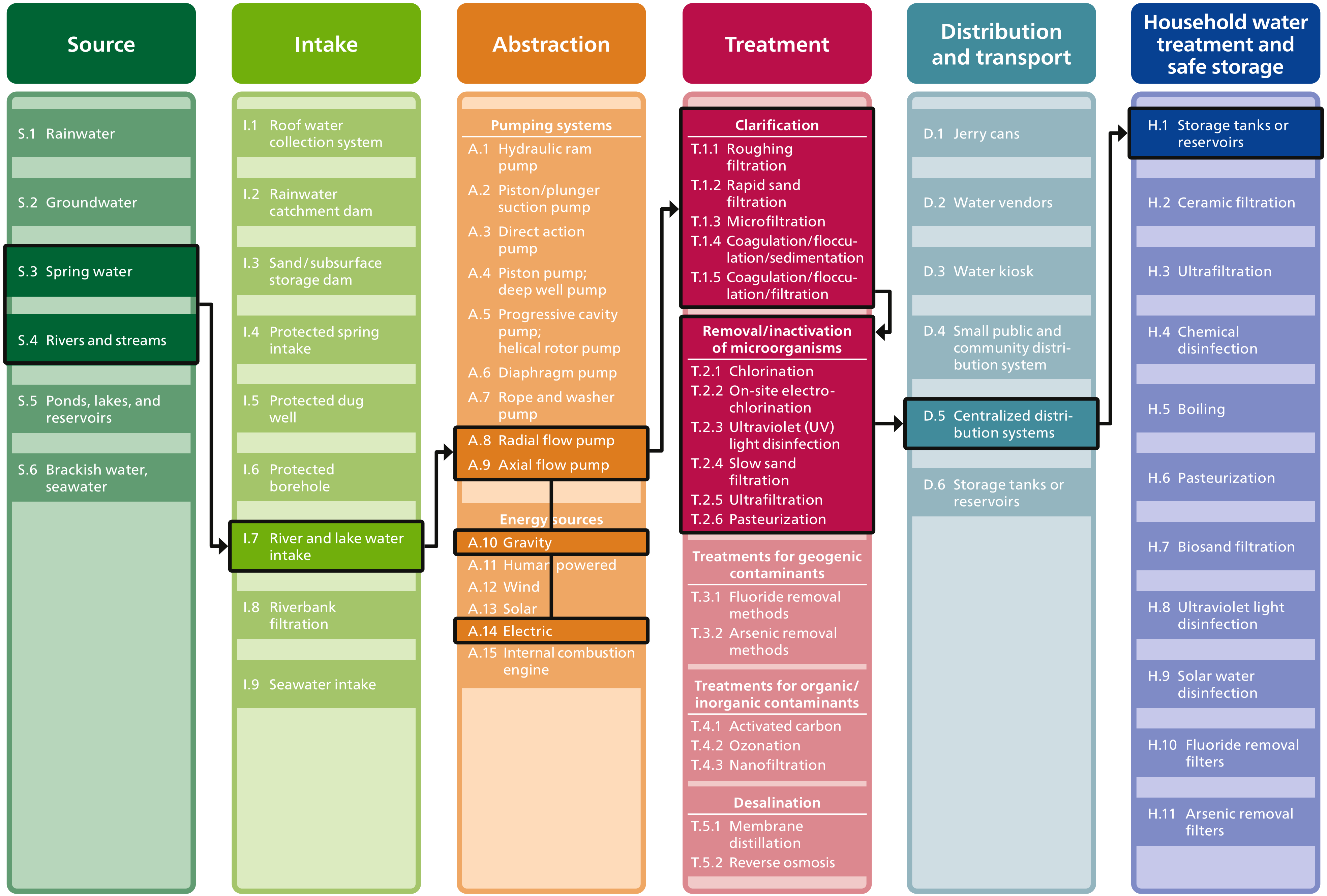
Often in centralized water supplies, the intake structures (see I.7 River and lake water intake) can adjust the depth of the water abstraction point (tower intake), which allows both the selective abstraction of higher quality water and the abstraction of water from variable levels (e.g. in the case 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 possible 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, followed by 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 residual water protection from microbial recontamination and bacterial re-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 the whole system is protected by adequate residual chlorine (i.e. ≥ 0.2 mg/L to the point of delivery to the consumer). 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 inspections); 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 revenue), 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) 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.

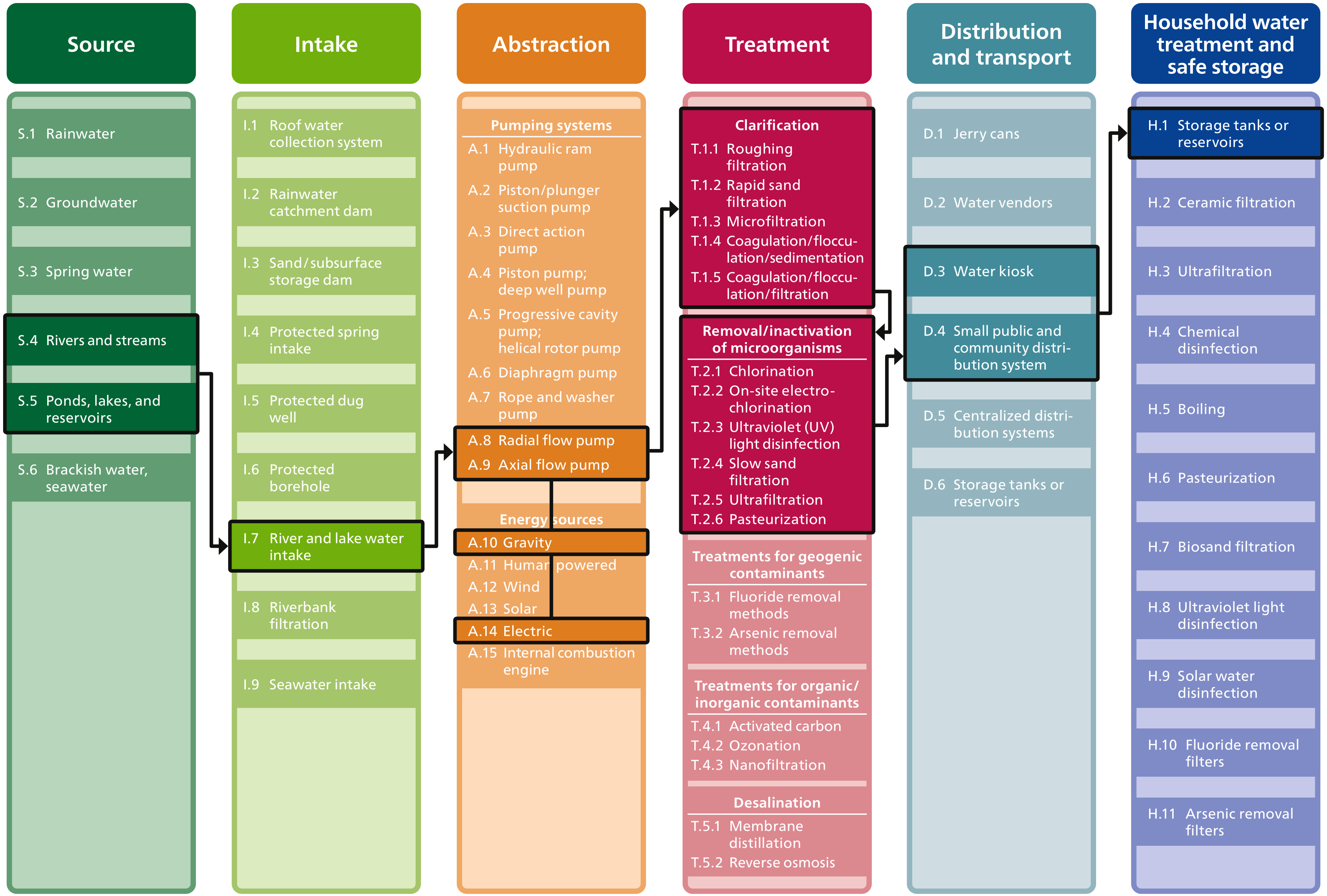
In decentralized community surface water supplies, smaller rivers or streams (see S.4 Rivers and streams) are often used. Thus, adequate waterbody flow and level are needed throughout the year, and the construction of a small submerged weir might be necessary to ensure an adequate water depth year-round. 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 concreate 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 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, as it provides an adequate residual concentration in the distribution system (i.e. ≥ 0.2 mg/L to the point of delivery to the consumer). 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). 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 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 usually pumped to an elevated storage reservoir from

System 3 Decentralized surface water treatment



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 infrastructures and need to account 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 revenue), 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 are for example, membrane filtration (see H.3 Ultrafiltration), biosand filtration (see H.7 Biosand filtration), or 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). 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).

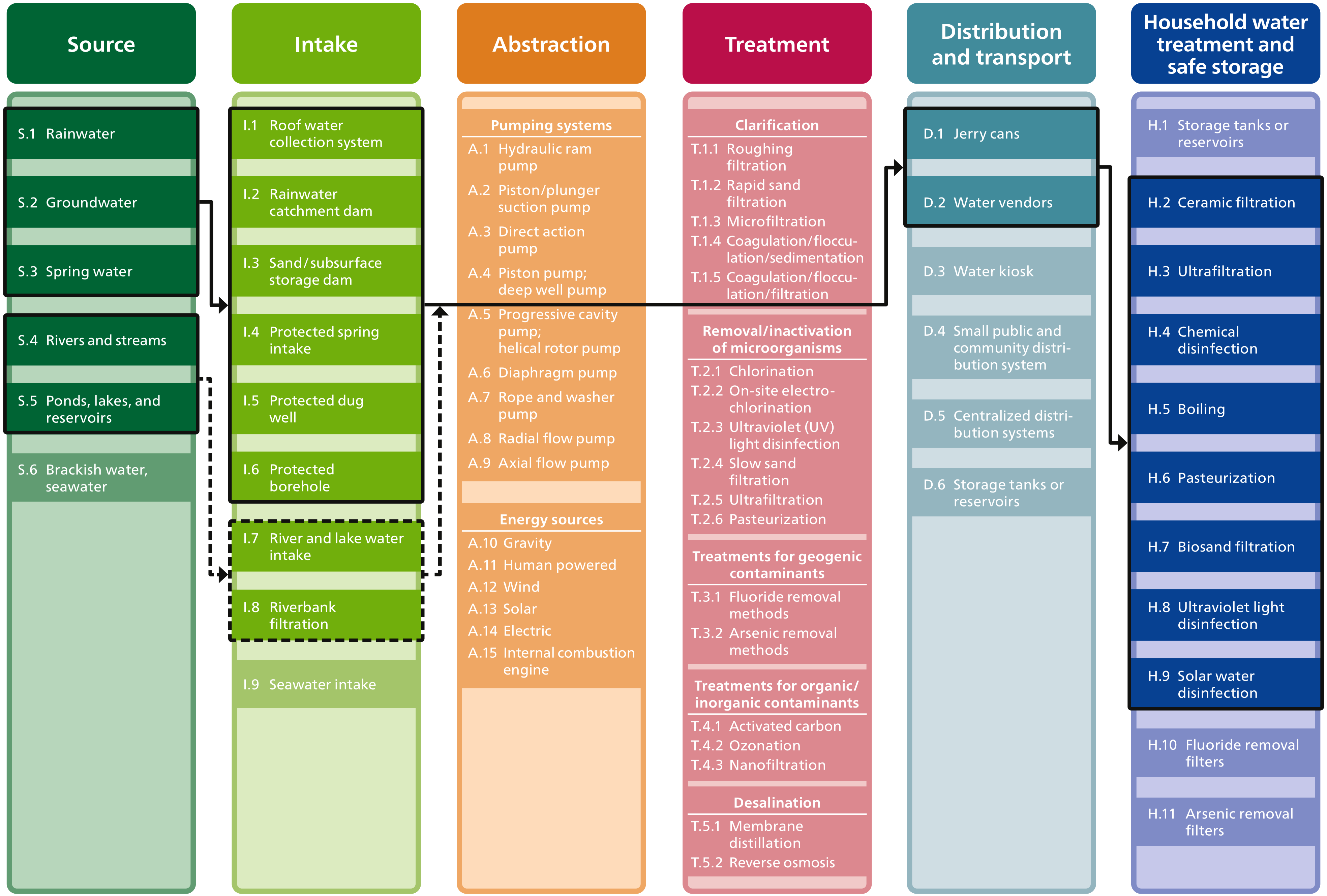
Considerations

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 behavior 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.

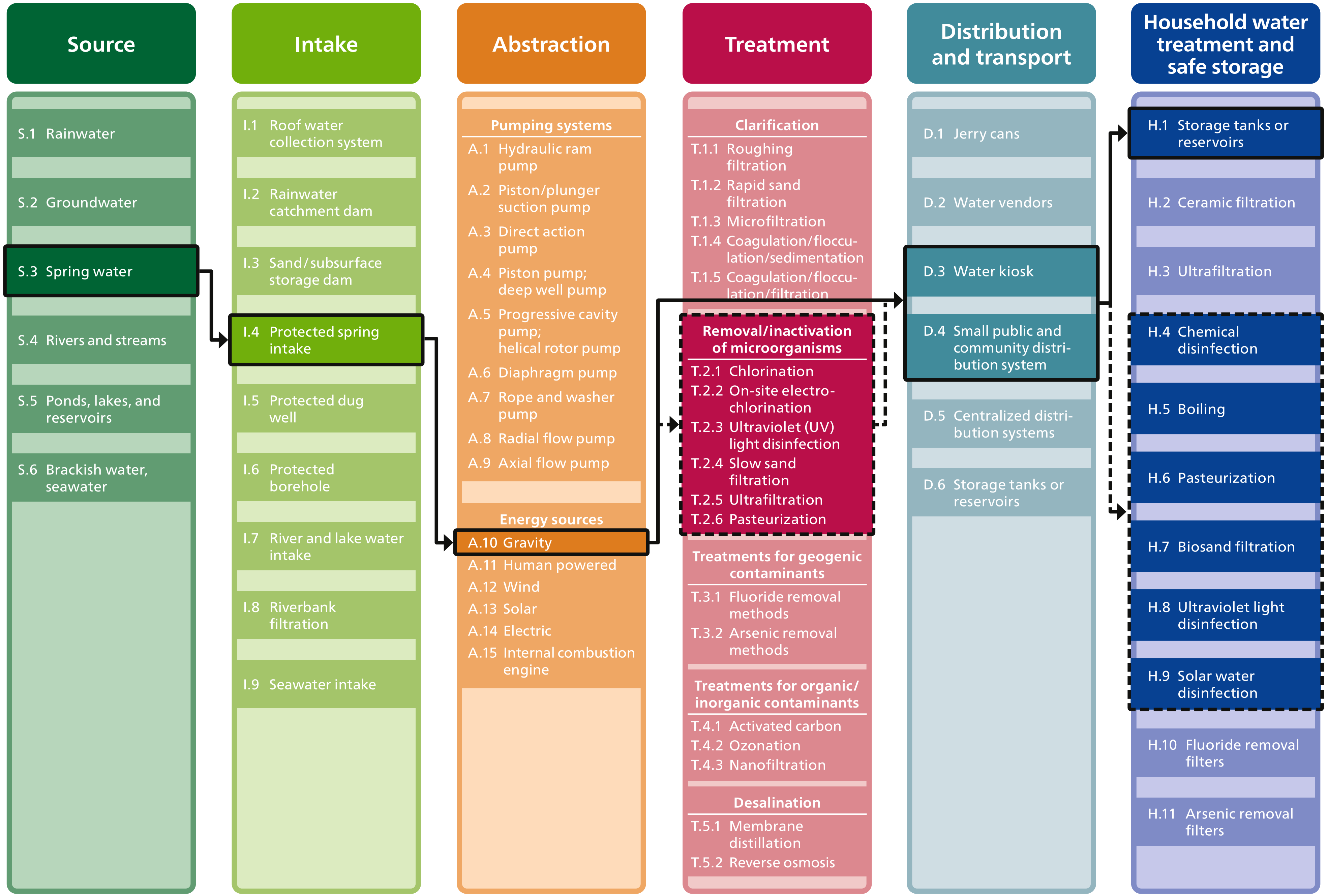
Considerations

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 assure 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.

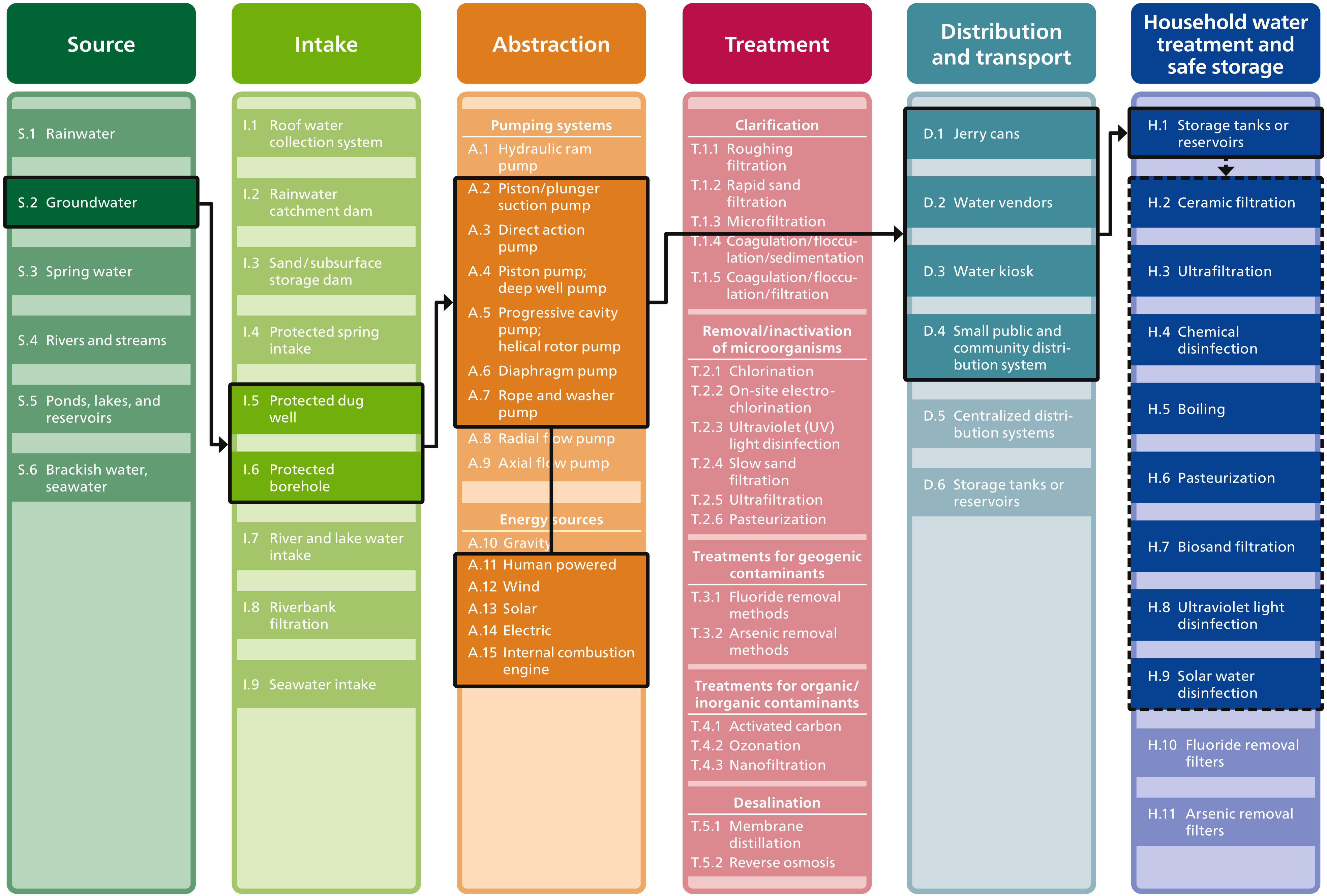
In areas with unreliable energy supply, safe water storage tanks (see H.1 Storage tanks or reservoirs) at households (e.g. rooftop, ground-level, or underground) can be used to cover for interruptions in the water supply.

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 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. The World Health Organization (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 drinking water guideline values are 0.01 mg/L for As,[1] 1.5 mg/L for F (WHO, 2017) and 0.08 mg/L for Mn (WHO, 2021).[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, odor, 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.

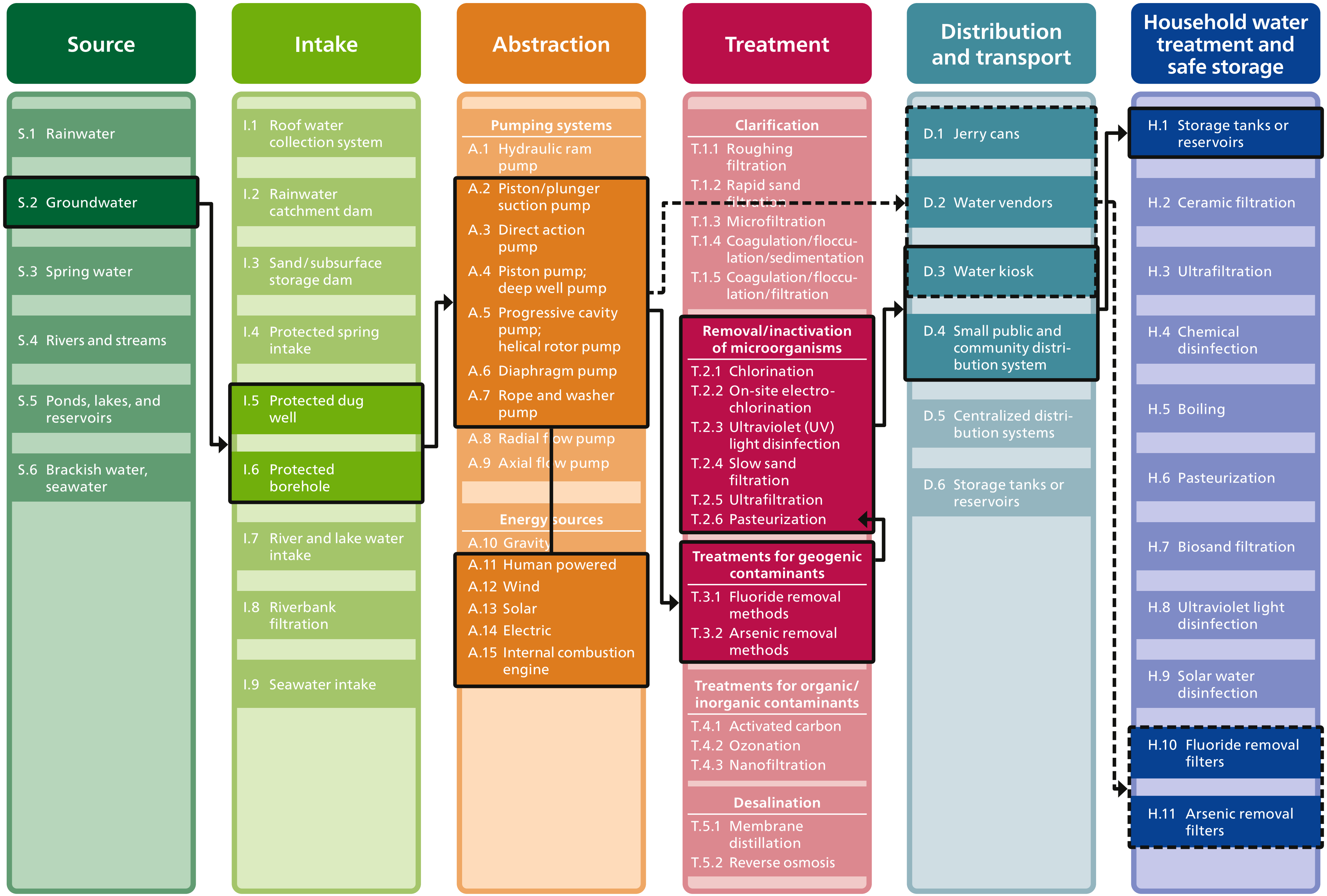
Considerations

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 due to uncertainties of health impacts at low exposure as well as practical difficulties in arsenic removal from drinking-water. 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 with for example chlorine (see T.2.1 Chlorination) is required. 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 World Health Organization (WHO) publications (2006) *Protecting groundwater for health* and (2016) *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 µg/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 (2012) *Pharmaceuticals in drinking-water*.

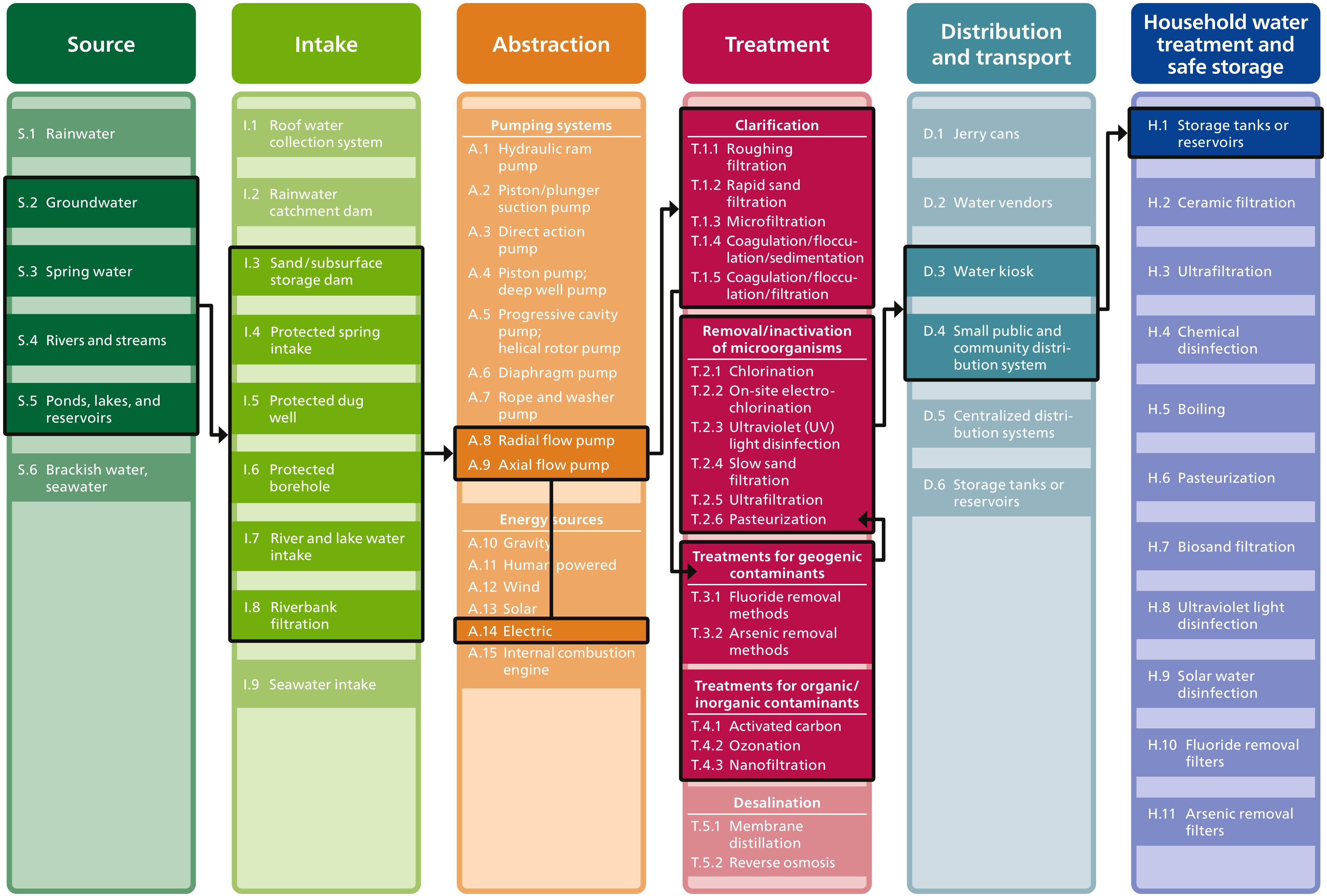
Considerations

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 Ultrafiltration) 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.

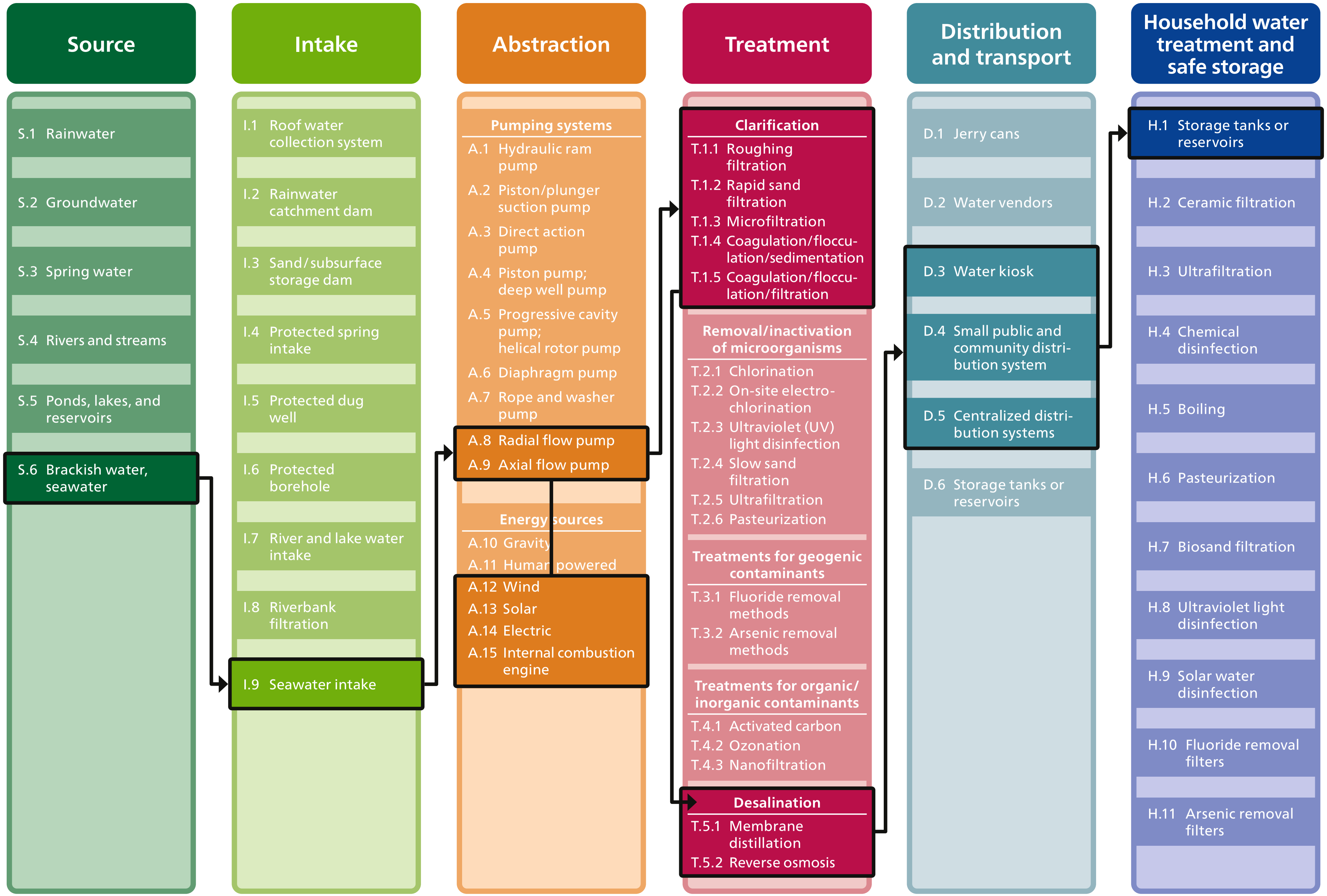
System designs have to consider the site-specific salinity and ion composition of the raw water to be desalinated, particularly to define the achievable recovery rates and optimum energy usage as well as to avoid the formation of salt deposits (scaling) in the desalination plant.

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.

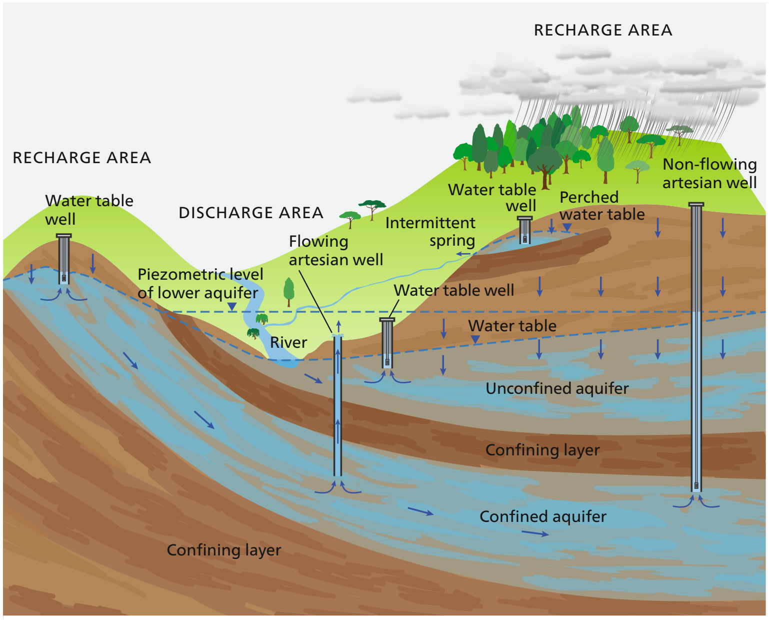
Desalination coupled with a solar power supply (see A.13 Solar) or wind power (see A.12 Wind) can be reliably operated in remote locations. If energy is generated by a diesel generator (see A.15 Internal combustion engine – diesel and petrol), low grade heat can be used to desalinate the water by thermal 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 assure reliable operation and maintenance.

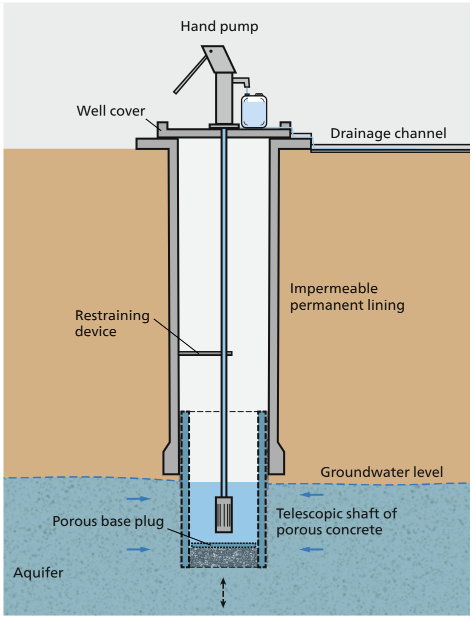
For further information on drinking-water quality considerations for salt water, refer to WHO (2011) *Safe drinking-water from desalination.*

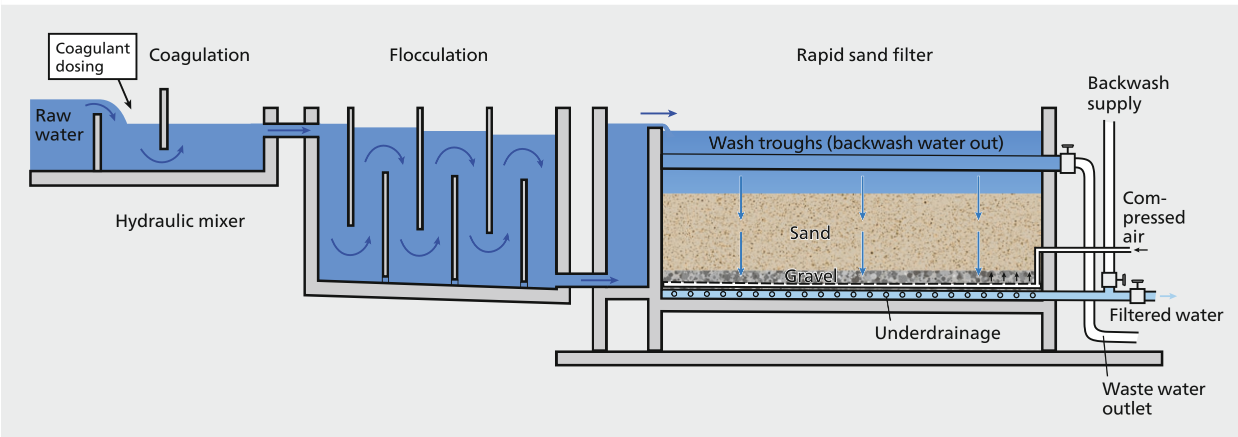
System 9 Desalination of brackish and salt water



Part 2 | Technology information sheets







Technology information sheets

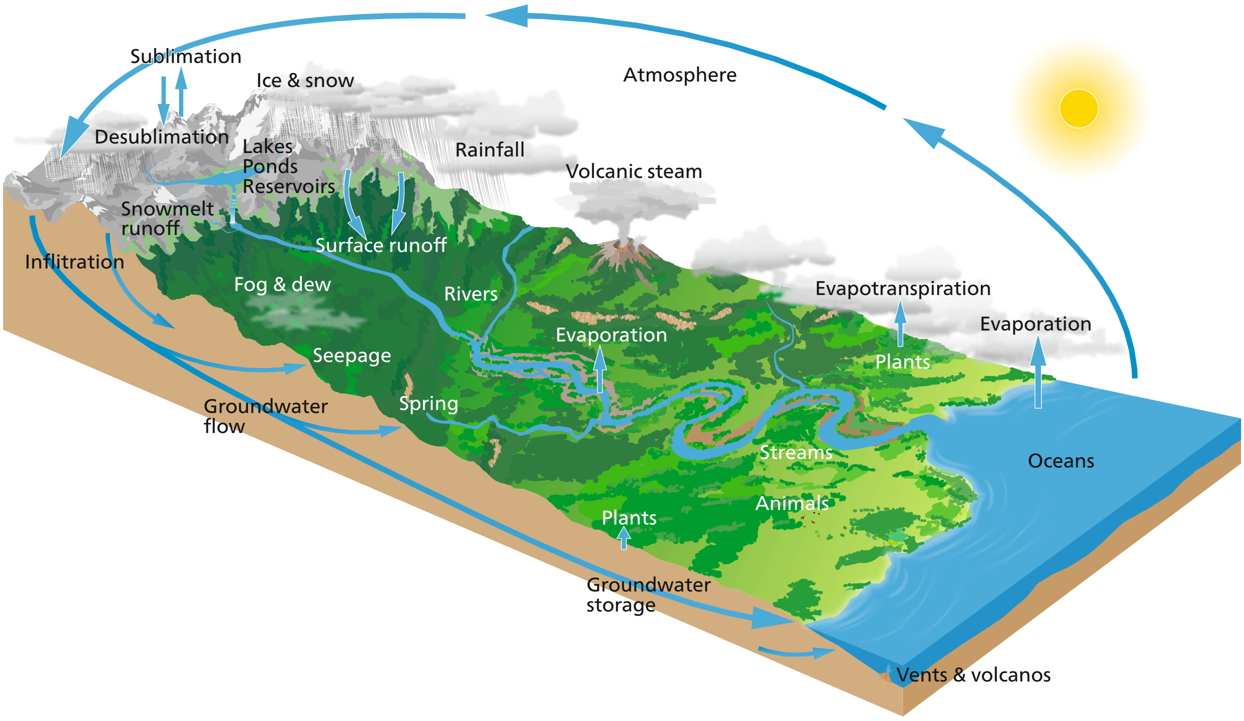
The second part of the Compendium provides an overview of the differing drinking water technologies within each functional group (Source, Intake, Abstraction, Treatment, Distribution and Storage, User Safety).

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 or 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.

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

Table 1
Technology information sheet summary table explained



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 the 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 avoid competition within the community.

When selecting any kind of water resource, an initial assessment should be conducted that considers the following factors:

- **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	Management level	Local availability	Technology maturity level
1, 4	–	–	–

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 fecal 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.2 Rainwater catchment dam). When exposed to light and with sufficient nutrients, algae (cyanobacteria) may grow in storage tanks, which can produce compounds with unpleasant taste and odor, 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 odor, which may negatively affect its acceptance as a drinking water resource.

Microbial contamination, such as through fecal 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

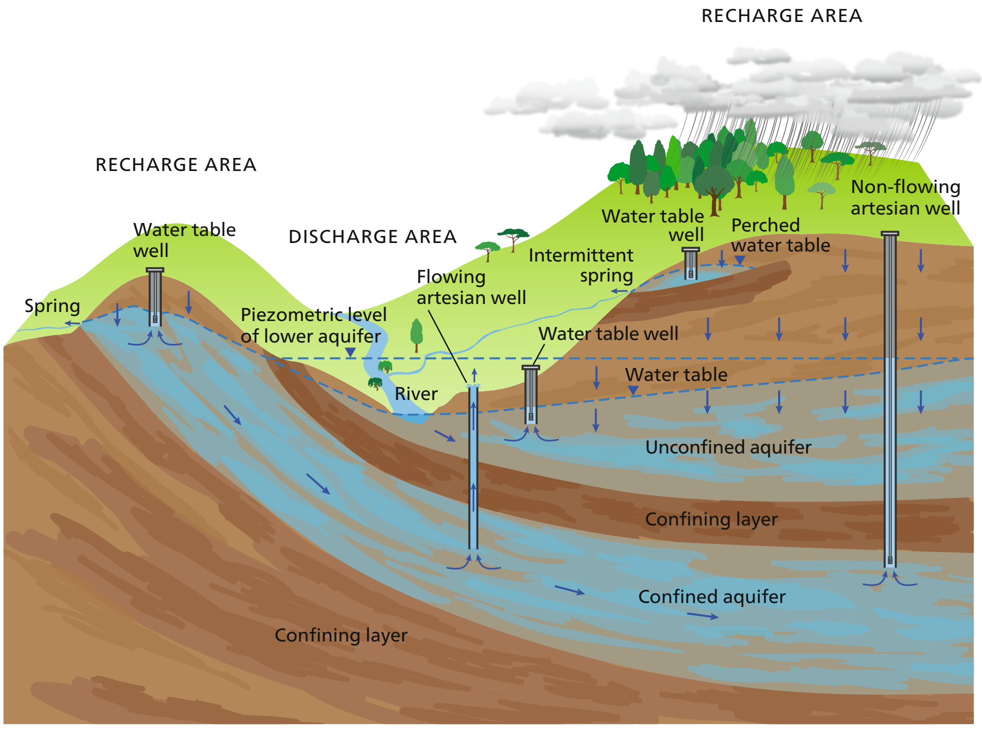
- Supply is limited by rainfall patterns over the year, the size of the rainwater capturing area, and storage capacity of the rainwater harvesting system
- Contamination of rainwater by air pollution, animal excreta, insects, dust, bushfire deposition, etc. is possible
- Acceptance can be hampered due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

→ References and further reading materials can be found on page $$$

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

S.2 Groundwater

Applicable to systems	Management level	Local availability	Technology maturity level
4, 5, 6, 7, 8	–	–	–



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

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 sis 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 IUCN publication (2016) *Managing groundwater sustainably*.

⊕ Advantages

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

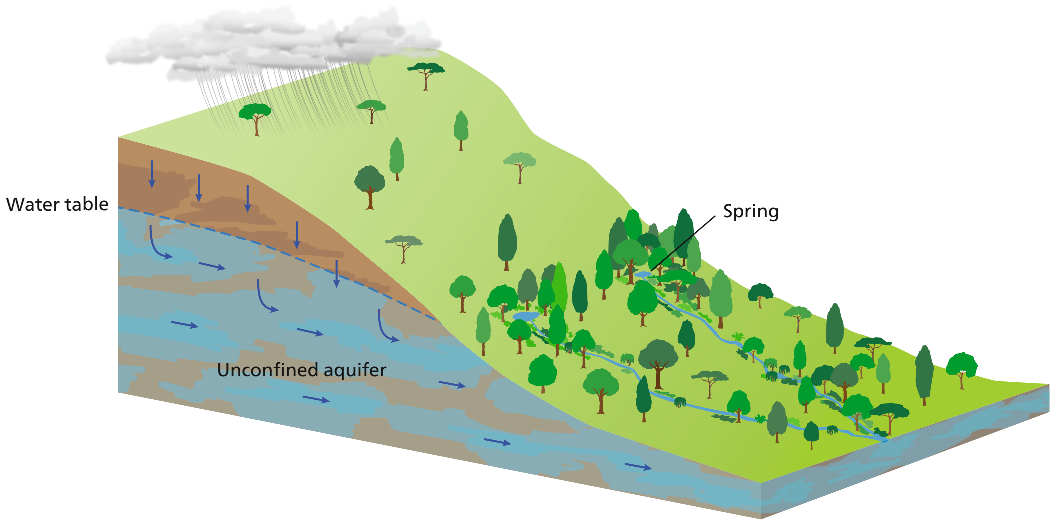
⊖ Disadvantages

- 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 page $$$

S.3 Spring water

Applicable to systems	Management level	Local availability	Technology maturity level
4, 5, 6, 7, 8	–	–	–



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 abstract infrastructure (although installation of a spring box may be needed). Since springs are generally located on hills, a simple gravity flow delivery 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, surface water 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, presence of animals/their faecal material in proximity to the spring, etc. 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
- Sometimes can be used for relatively simple gravity water supplies without pumps

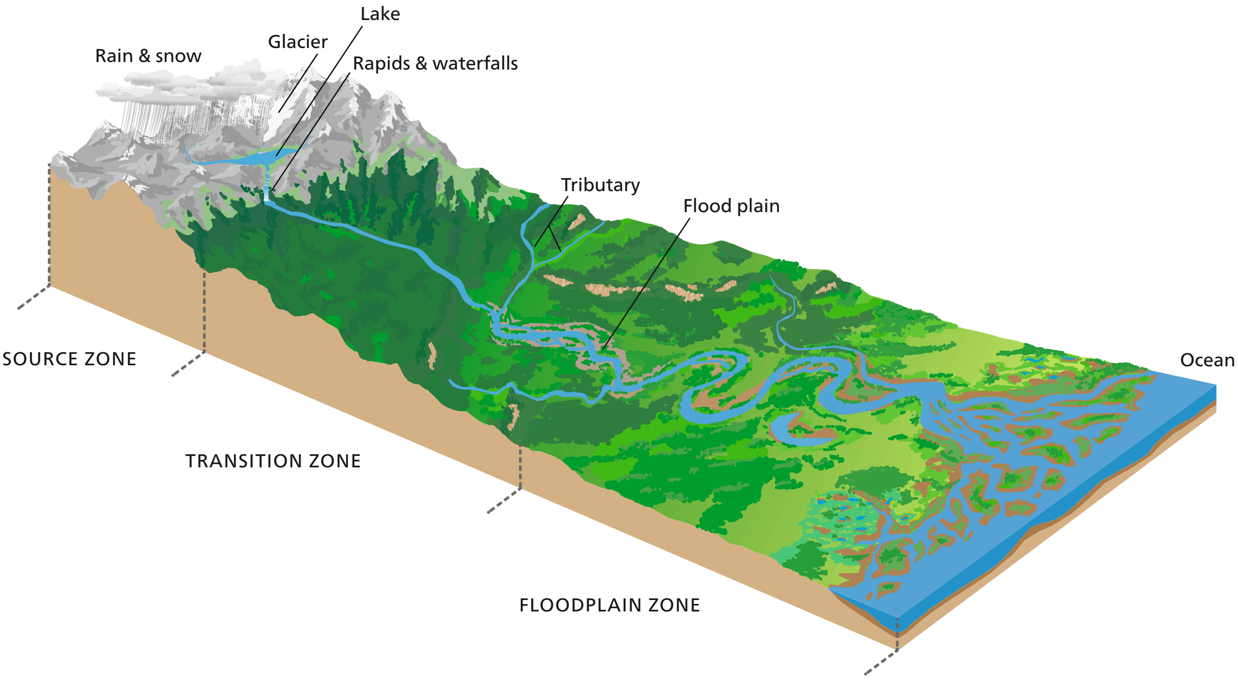
⊖ Disadvantages

- Quantity of water from springs can be susceptible to seasonal variation and water table fluctuations
- Depending on soil structure and other 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 $$$

S.4 Rivers and streams

Applicable to systems	Management level	Local availability	Technology maturity level
2, 3, 4, 8	–	–	–



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

Per definition, 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, 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 is likely through the poor sanitation practices (e.g. open defecation, discharge of raw effluent or inadequately treated sewage) and/ or surface run-off from surrounding anthropogenic activities including agriculture, and/or industrial activity within the river's catchment. An extensive overview of potential hazards in surface water catchments and their management is given in the WHO publication (2016) *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.

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 (decline in biodiversity, mosquito breeding, etc.).

⊕ Advantages

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

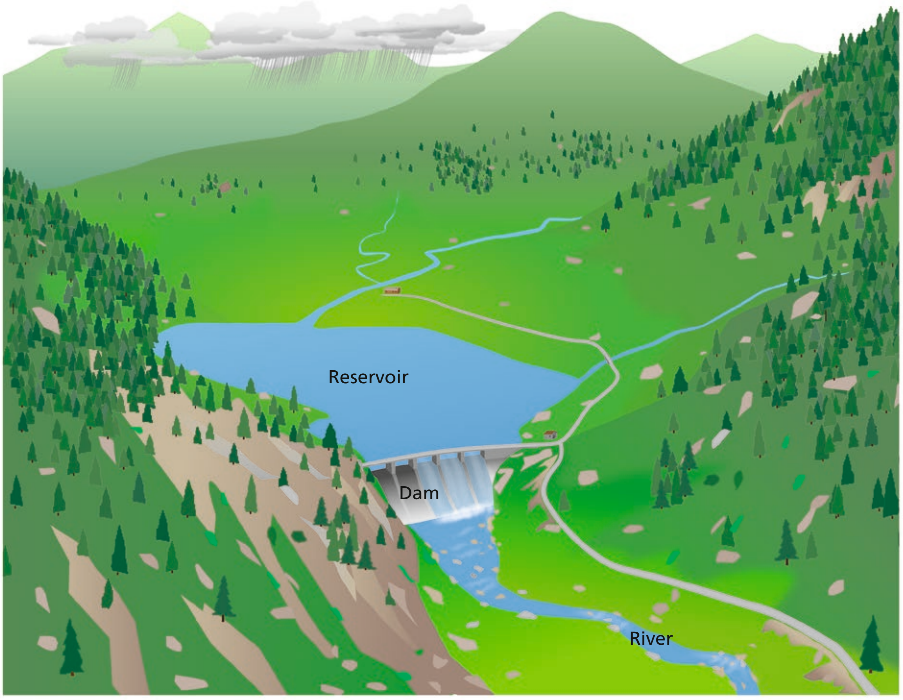
⊖ Disadvantages

- 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 $$$

S.5 Ponds, lakes, and reservoirs

Applicable to systems	Management level	Local availability	Technology maturity level
2, 3, 4, 8	–	–	–



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 2,500 mm. In cooler, more humid areas, annual evaporation is less than 1,000 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 fecal 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 (2016) *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 odor 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.

⊕ 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

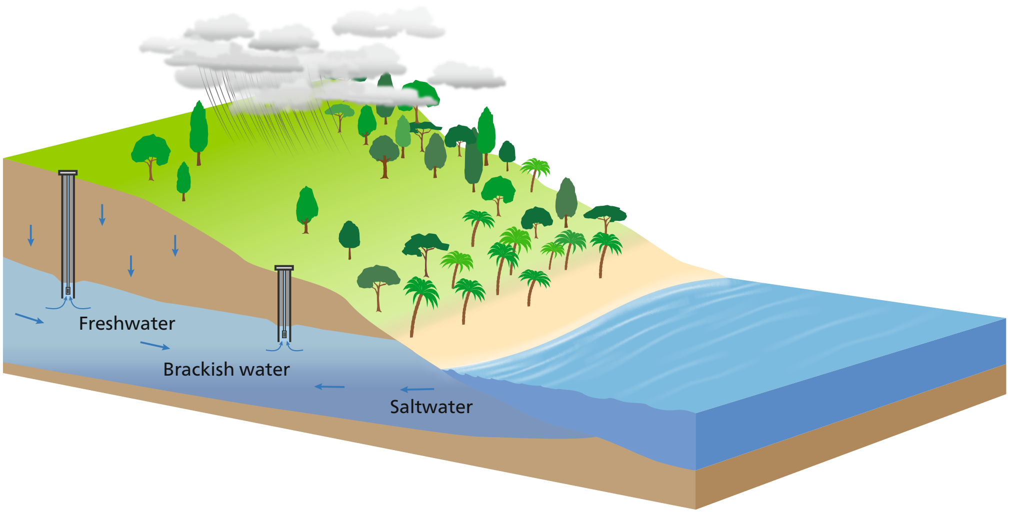
⊖ Disadvantages

- 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 $$$

S.6 Brackish water, seawater

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



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 liter 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 1,000 mg/L. Brackish water forms by the mixing of freshwater with seawater and is characterized by TDS concentrations between 1,000 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 (remineralization) 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 due to the fact that desalination technologies are expensive since they require a lot of energy, with the treatment of seawater more expensive than brackish water because of 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 the local energy costs, but overall costs to produce freshwater from saltwater are higher than 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 $$$

I Intake

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

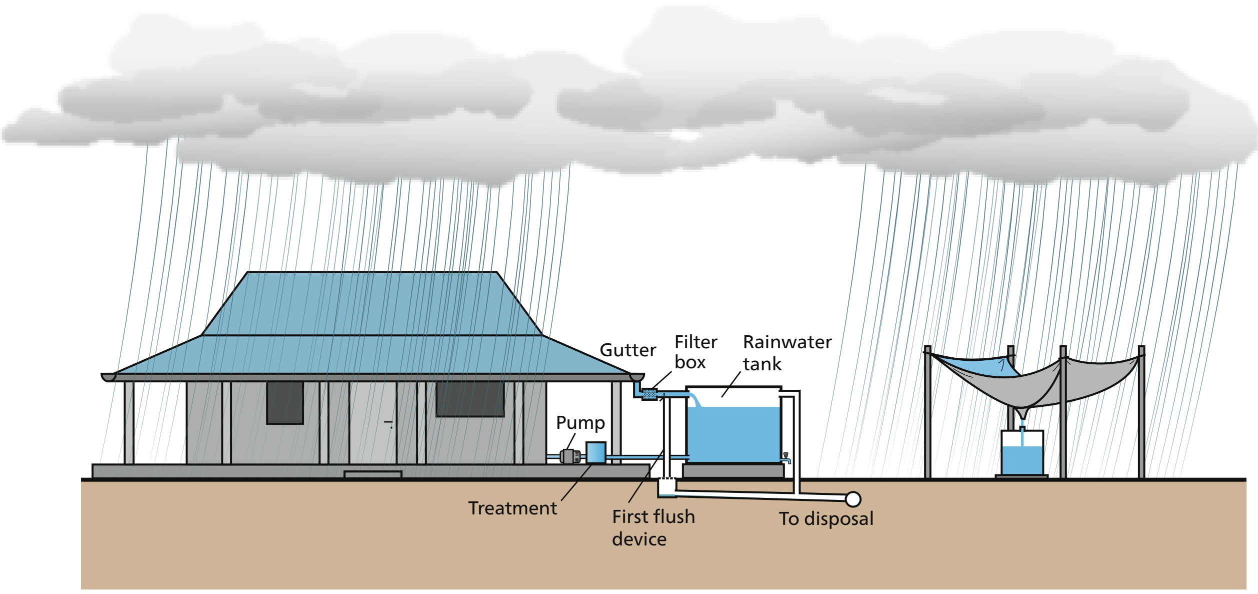
I.9 Seawater intake

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 year-round water supply is needed and a larger catchment area must be used. 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 (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.

I.1 Roof water collection system

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
1	Household, school, health center, community	Mostly	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:

Supply (L/year) = Rainfall (mm/year) × Roof Area (m²) × 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 fecal 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 present mosquito-breeding sites if the tanks are not adequately covered.

Rainwater lacks minerals like calcium and magnesium, and thus lacks a particular taste. However, during storage, rainwater can develop taste and odor, which may negatively affect its acceptance as a drinking water resource. Most common taste and odor issues arise through small dead animals, sediments, biofilms (or "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 or 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 tanks or tanks installed on the ground
- Low capital cost
- Low operating costs
- Long service life
- Individual household ownership and responsibility
- Water is often available where needed

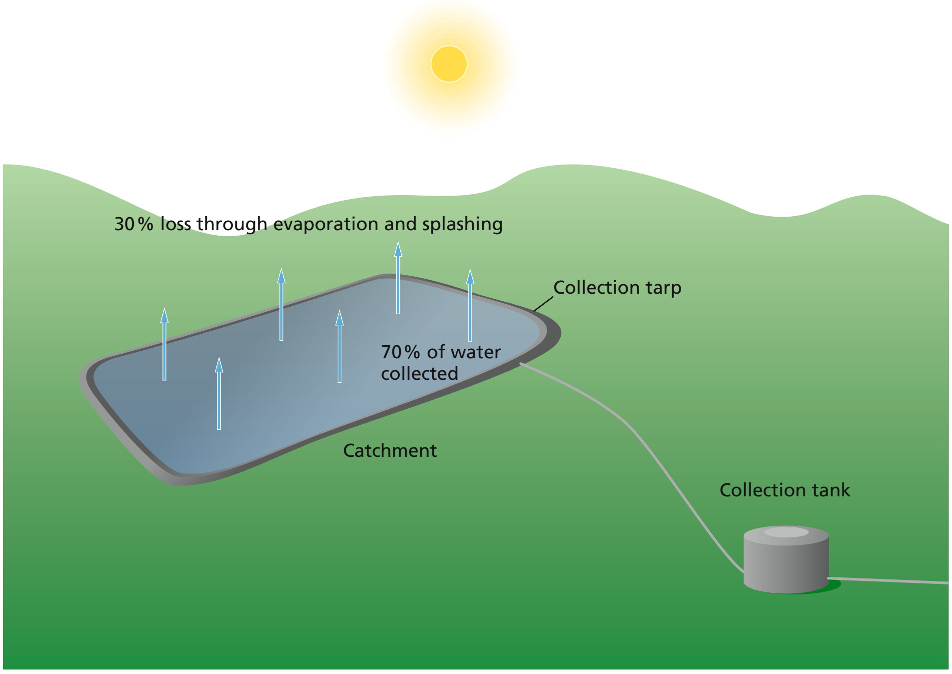
⊖ Disadvantages

- 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 $$$

I.2 Rainwater catchment dam

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 4, 5, 8	Community, centralized	Yes	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 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. Usually, a valve is 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, they 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 sources 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 downstream 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 fecal 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 toilet facilities in the catchment can lead to water contamination, and watershed protection measures are indispensable for ensuring water safety for multiple uses. Fencing the dam and reservoir can prevent livestock access and reduce the risk of fecal contamination. Water safety plans may prove useful for ensuring 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 $$$

I.3 Sand/subsurface storage dam

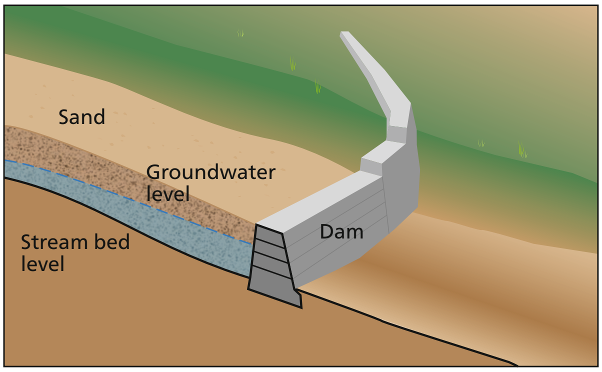
Applicable to systems
4

Management level
Community

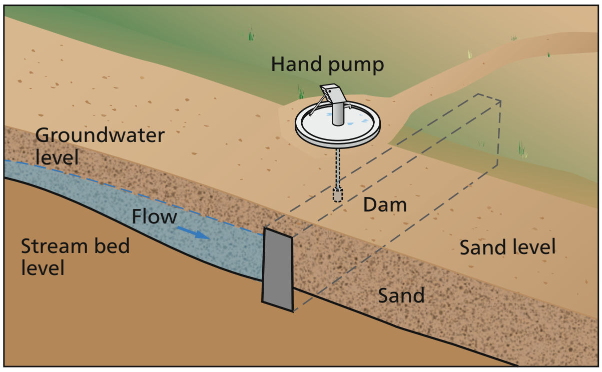
Local availability of technology or components
Yes

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 tap could weaken the dam structure if not properly constructed.

Subsurface storage dams are built entirely below the earth's surface, where they hinder the flow of groundwater. The crest of the subsurface dam is recommended to be 1 m 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 improves 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 life span 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).

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
- 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

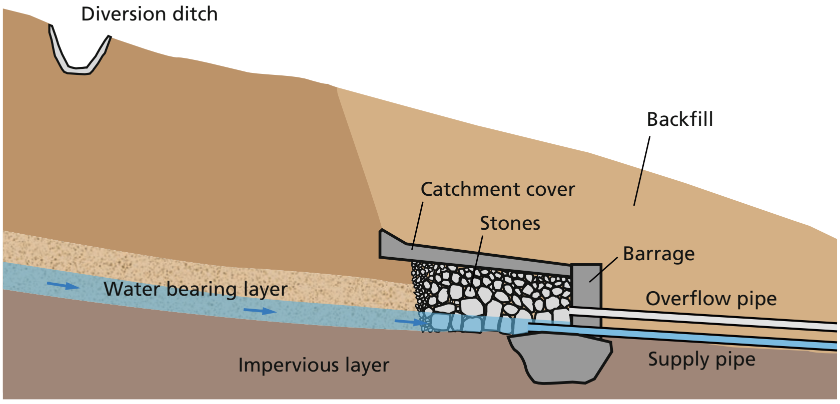
⊖ Disadvantages

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

→ References and further reading materials can be found on page $$$

I.4 Protected spring intake

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
4, 5, 6, 7, 8	Community	Yes	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 meters 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 SKAT publication *Spring Catchment* (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 meters) 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 meters deep or 30 meters 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.

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

→ References and further reading materials can be found on page $$$

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 Annex 2 of the Guidelines for drinking-water quality, 2nd edition: Volume 3 - Surveillance and control of community supplies (WHO, 1997).

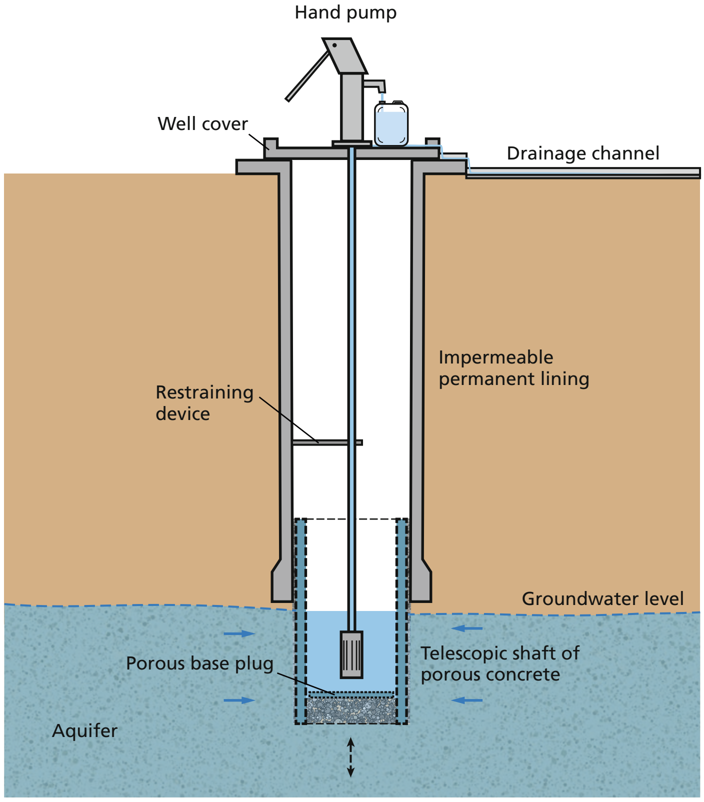
I.5 Protected dug well

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 0.8 m up to 15 m. Depths range from < 5 m (shallow dug well) to > 20 m (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 recharge of the well.

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 3 m 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 1–4 m 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 abstracting impaired groundwater, 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* (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 SKAT publication *Hand-dug shallow wells* [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* (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

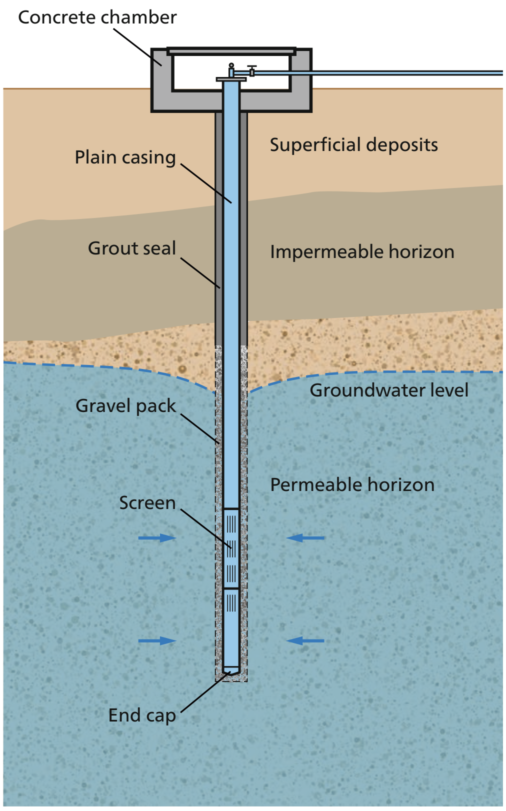
→ References and further reading materials can be found on page $$$

5 For guidance on determining appropriate minimum safe distances for potentially contaminating activities, refer to Annex 2 of the Guidelines for drinking-water quality, 2nd edition: Volume 3 - Surveillance and control of community supplies (WHO, 1997).

6 For guidance refer to https://www.who.int/water_sanitation_health/publications/2011/tn1_cleaning_disinfecting_wells_en.pdf

I.6 Protected borehole

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
4, 6, 7, 8	Household, community, centralized	Mostly	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* (2001) .

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 groundwater quality depends on local hydrogeology, its location relative 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 (e.g. seasonal and after flooding events) disinfection of the borehole may be required (e.g. via chlorination).[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* (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 and cheap drilling technologies are available

⊖ Disadvantages

- Siting and drilling require considerable expertise and costly equipment
- Pump maintenance requires expertise/training and access to tools/parts

→ References and further reading materials can be found on page $$$

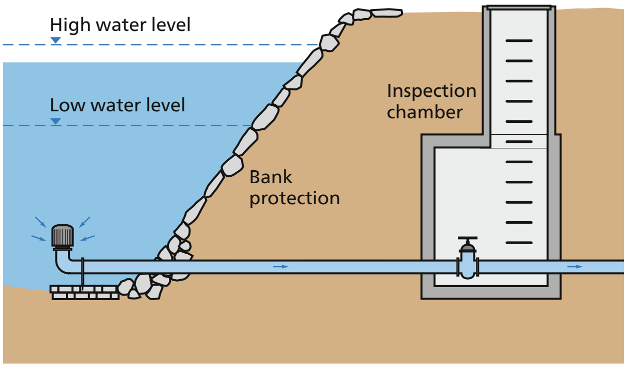
7 For guidance on determining appropriate minimum safe distances for potentially contaminating activities, refer to Annex 2 of the Guidelines for drinking-water quality, 2nd edition: Volume 3 - Surveillance and control of community supplies (WHO, 1997).

8 For guidance refer to https://cdn.who.int/media/docs/default-source/wash-documents/who-tn-02-cleaning-and-disinfecting-boreholes.pdf?sfvrsn=5922a413_4

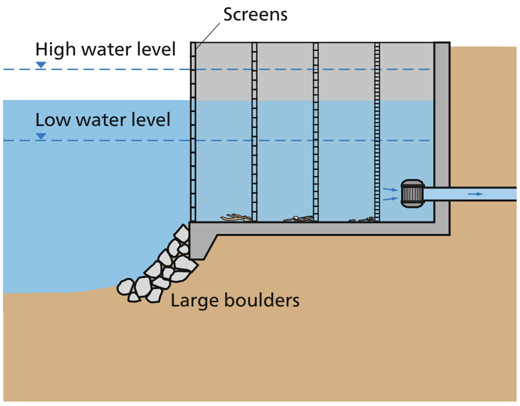
I.7 River and lake water intake

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 4, 8	Community, centralized	Mostly	Established technology

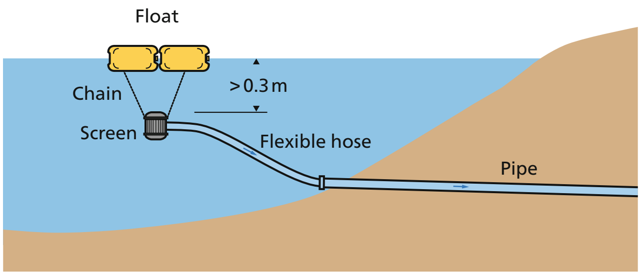
UNPROTECTED INTAKE



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 fecal 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

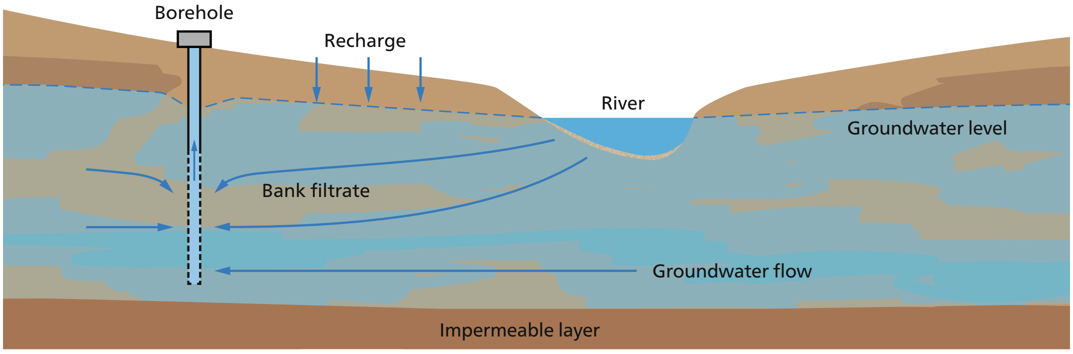
⊖ Disadvantages

- 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 $$$

I.8 Riverbank filtration

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 4, 8	Community, centralized	Mostly	Established technology



Riverbank filtration is a water abstraction technology that pumps water from boreholes that are typically drilled within a few hundred meters 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 meters 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 filtrations 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* (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

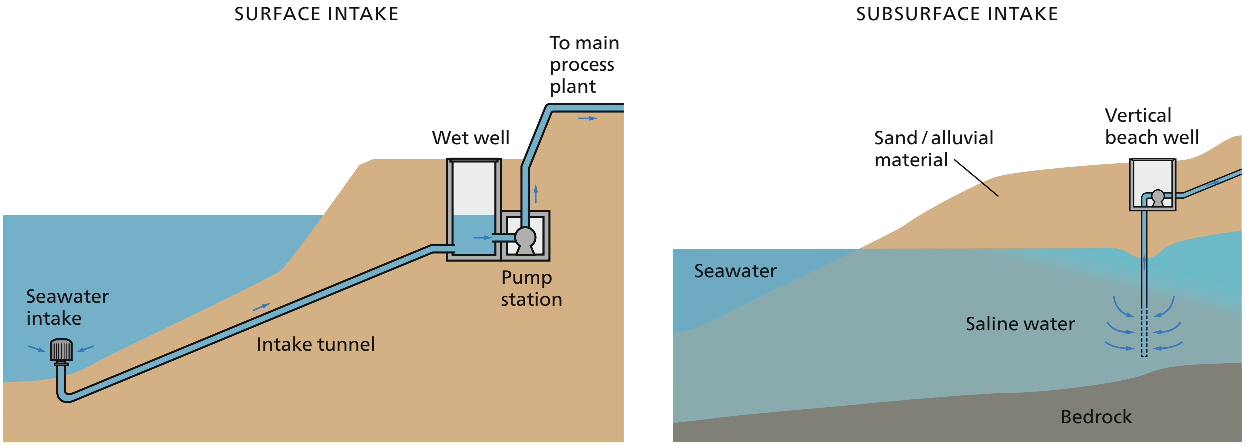
⊖ Disadvantages

- 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 page $$$

I.9 Seawater intake

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
9	Centralized	Sometimes	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 meters into the ocean. Open surface intake structures have a life span 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 4,000 m³/day. The lifespan of beach wells is expected to be 15–20 years. Subsurface intakes naturally pretreat 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 (financially and timely). 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 (bacteria, viruses, algal toxins) in the treated water.

Surface structures:

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

⊖ Disadvantages
- Impingement and entrainment risks are high

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 $$$

A Abstraction

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), and the different sub-types are 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.

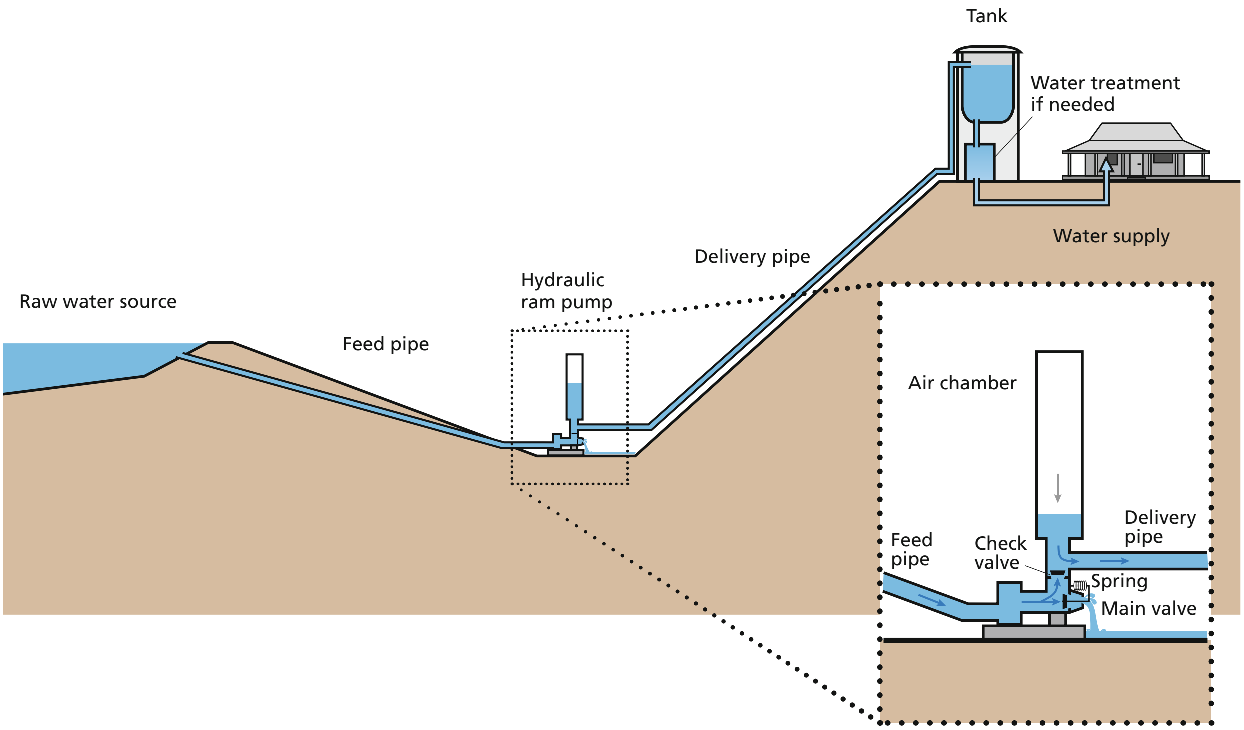
For groundwater or surface water at elevations lower than the treatment works, storage facilities, or consumers, pumping is required.

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 make more economic sense over time, since there are fewer ongoing 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	Management level	Local availability of technology or components	Technology maturity level
3, 5, 6	Community with appropriate technical support / centralized	Sometimes	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 heights 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.

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
- Are robust machines, due to few moving parts, and are also easy to maintain under local conditions

⊖ Disadvantages

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

→ References and further reading materials can be found on page $$$

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

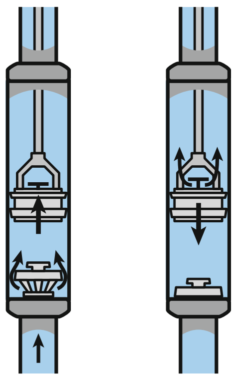
Applicable to systems
1, 3, 6, 7
(for water lifts up to 7 m)

Management level
Household/school/neighborhood/community/health center; technical support required for high-tech components

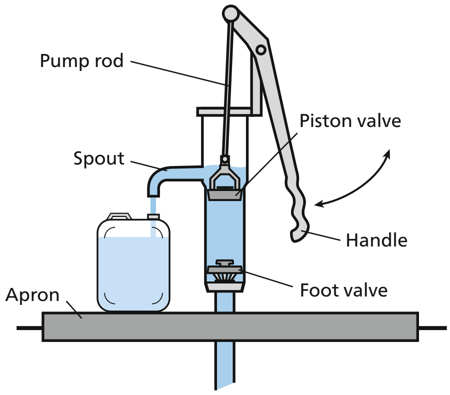
Local availability of technology or components
Sometimes

Technology maturity level
Established technology

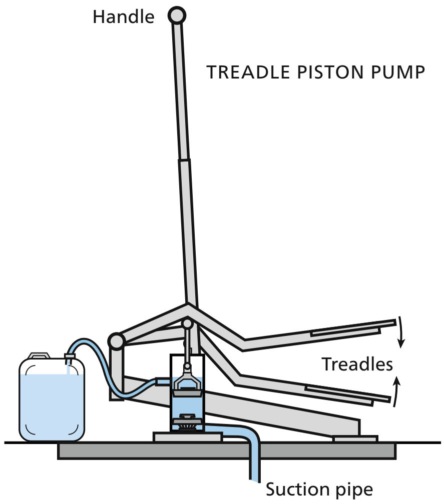
PISTON PUMP OPERATION



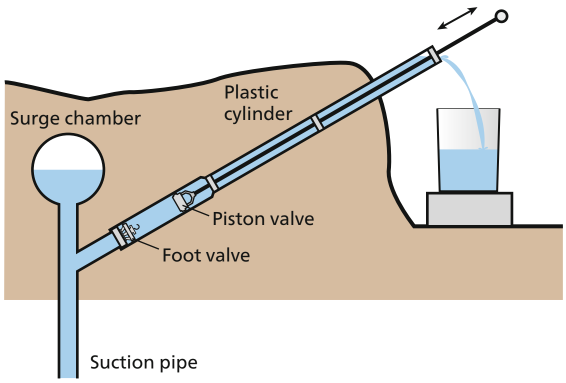
PISTON PUMP



TREADLE 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 2,400 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 3,000–4,500 L/h or 0.83–1.25 L/sec at 5 m depth) compared to non-suction types (2,500–3,000 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 1,000 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, highly 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 occur where metal components are used in conjunction with groundwater with a pH of less than 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 has a pH of 6.5 or less, 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 color 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 7 m at sea level (less at higher altitudes)

→ References and further reading materials can be found on page $$$

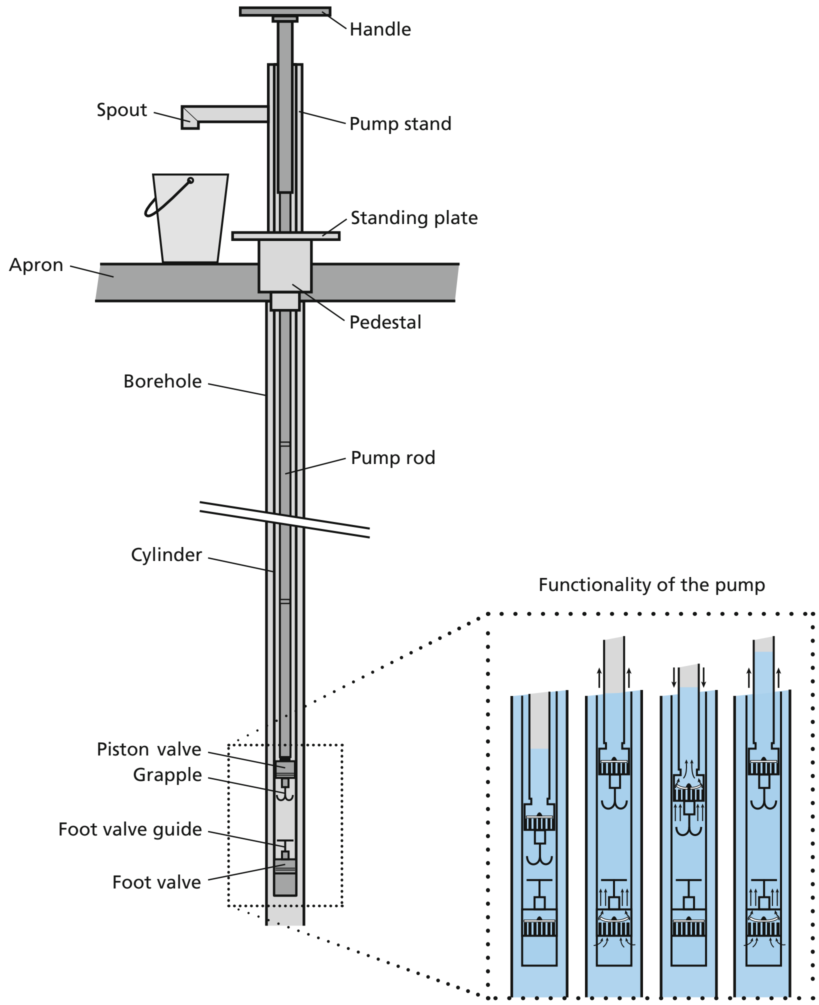
A.3 Direct action pump (Positive displacement pump)

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 15 m). 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 12 m.

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 5 m below the surface. However, children may experience difficulty in operating the pump with depths of greater than 5 m.

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, the 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 over-exertion – since water has to be lifted directly, this could cause back issues for adults, and 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 15 m of operating lift
- Can be physically hard work to operate, especially for children or the elderly

→ References and further reading materials can be found on page $$$

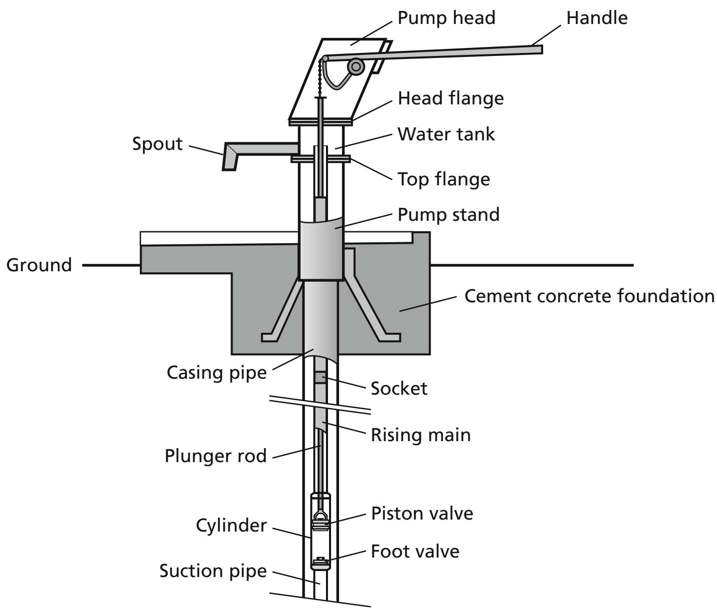
A.4 Piston pump; deep well pump (Positive displacement pump)

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. Manufacture has recently become more centralized (particularly in India)

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 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 an 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 locals. 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. Annually, the pump should be dismantled and checked.

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 microbial contamination of 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 has a pH of 6.5 or less, 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

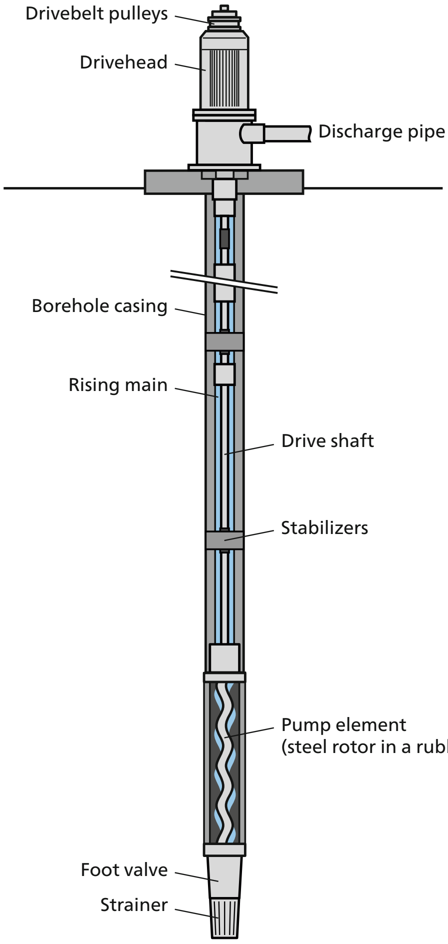
⊖ Disadvantages

- 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 $$$

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

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
1, 3, 4, 6, 7, 8 (for water lifts of 2–300 m)	Community, technical support required	Well-proven and robust motorized system used in suction pumps as well as in submersible pump systems; available from renown international pump suppliers	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", named after the inventor, Rene Moineau.

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 m) 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 300 m 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 pump (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 it 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 contact groundwater with a pH of less than 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 microbial contamination of 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 has a pH of 6.5 or less, 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

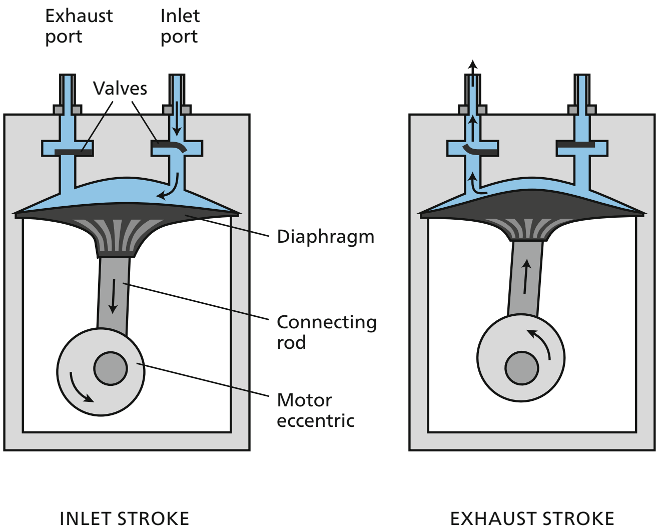
⊖ Disadvantages

- 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 the marketplace
- Running against a closed valve can damage pump and fittings

→ References and further reading materials can be found on page $$$

A.6 Diaphragm pump (Positive displacement pump)

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
3, 6, 7 (for water lifts of 2–60 m)	Community; technical support required	Available as submersible pump or surface pump in most countries; in some areas, manually operated versions are also available mainly for shallow water lifts	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 pumped 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 (e.g. Vergnet). 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 local should be appointed as a caretaker and trained to carry out the required day-to-day operation and maintenance tasks. The pump head, platform, and surroundings must 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 village 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 microbial contamination of 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
- Locals can operate and perform minor maintenance

⊖ Disadvantages

- Requires trained service technicians for repairs
- Can have costly and time consuming repairs if the repair service is not available locally.
- May not be possible to operate by elderly, children, and pregnant women due to the large forces required

→ References and further reading materials can be found on page $$$

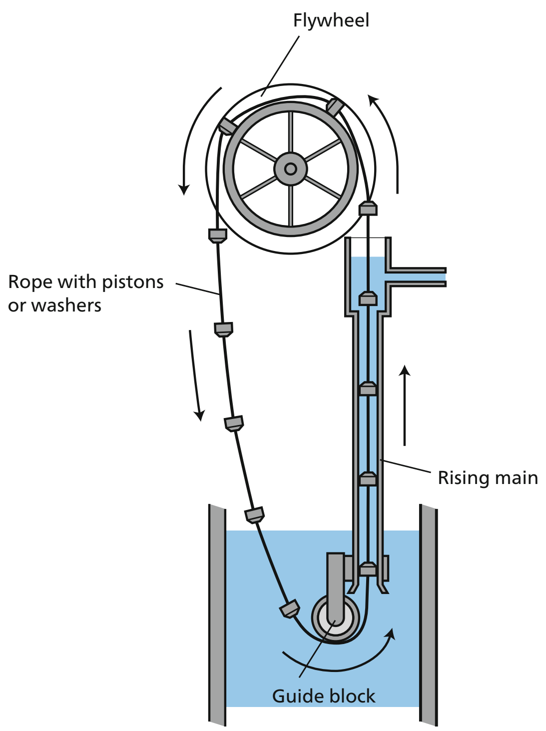
A.7 Rope and washer pump (Positive displacement pump)

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 give around 5,000 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 give 1,100 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 water and small-scale productive use 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 locals, 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 handpumps, 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 purchase and maintain
- Can be manufactured locally

⊖ Disadvantages

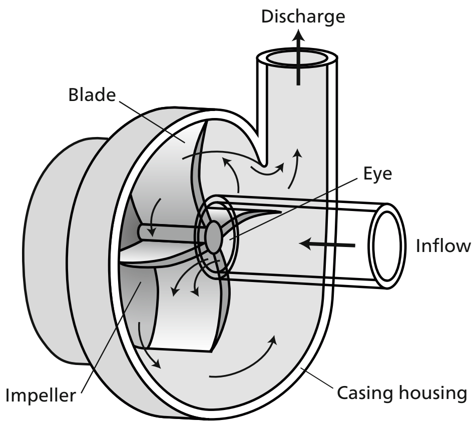
- Serves only small communities when manually operated
- Requires significant effort for manual operation of rope pumps with a lift of more than 5 m
- Has possible risk of contamination through touching the rope
- Has no foot valve, meaning each time pumping is started, the raising main needs to again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

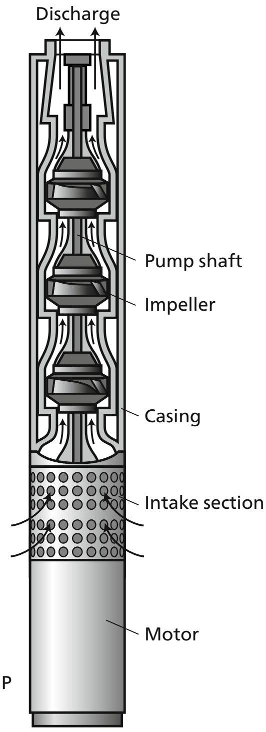
→ References and further reading materials can be found on page $$$

A.8 Radial flow pump (Centrifugal pump)

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 6, 7, 8, 9 (for water lifts of 10–600 m)	Community/centralized; technical support required	Radial flow water pumps are produced in huge numbers worldwide by numerous companies	Established technology

SINGLE STAGE CENTRIFUGAL PUMP





MULTISTAGE SUBMERSIBLE PUMP

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 an 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 when it is in contact with groundwater with a pH of less than 6.5, corrosion is more likely 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 has a pH of 6.5 or less, 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 aggressive groundwater 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

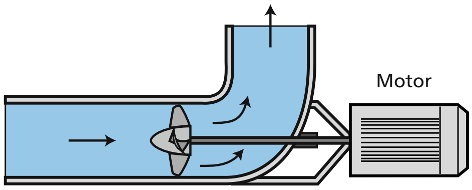
⊖ Disadvantages

- 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 $$$

A.9 Axial flow pump (Centrifugal pump)

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 8, 9 (for water lifts of 2–12 m; maximum 15 m)	Centralized, technical support required	Widely available for low lifts in most countries; produced by large companies and small workshops	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 meters or more in diameter and are usually designed as single-stage pumps. Multi-stage pumps can be employed 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.

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

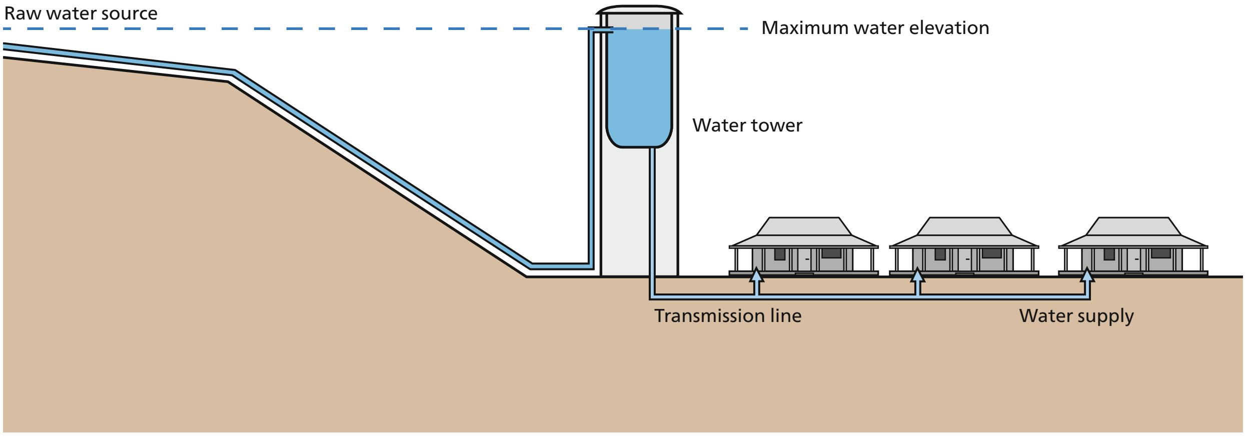
⊖ Disadvantages

- 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
- 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 $$$

A.10 Gravity (Energy source)

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
1, 2, 3, 5, 6, 8	Community/centralized	Mostly (local availability sometimes problematic)	Established technology



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 free, so 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 be 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 pipeline, 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 meters and is given as the energy per unit weight of water.

When a tap is opened, water flows, and 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 meters friction loss per 100 m 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 lifecycle 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 local people 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 abovementioned 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 lifecycle 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 $$$

A.11 Human powered (Energy source)

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
4, 6, 7	Household/school/neighborhood/community/health center	Mostly	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 a 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 finished with a pump 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 appropriate 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, over one-fifth of manually operated pumps are still 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 hardware, or acquiring 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.

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 10 m 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

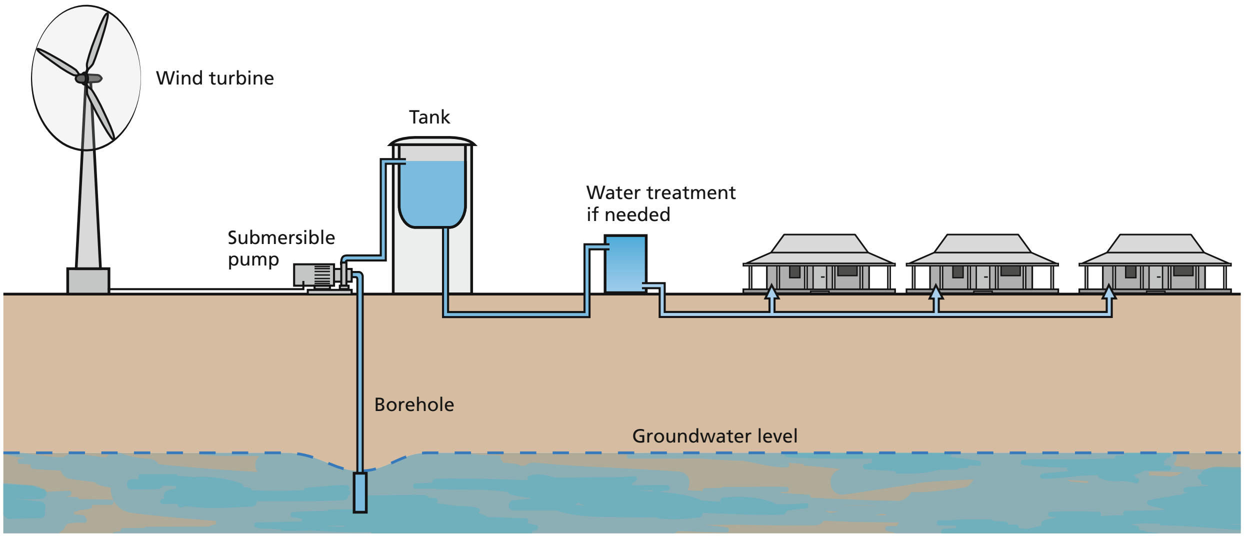
⊖ Disadvantages

- 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 the ill or under-nourished
- Causes thermal stress in hot weather and other health risks, such as physical and protection hazards
- Tends to contribute to gender inequality

→ References and further reading materials can be found on page $$$

A.12 Wind (Energy source)

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
4, 6, 7	Household/school/neighborhood/community/health center	Sometimes	Long established technology



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 I.6 Proected 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 (to get 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 meter (m^2) 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 analyzed. 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

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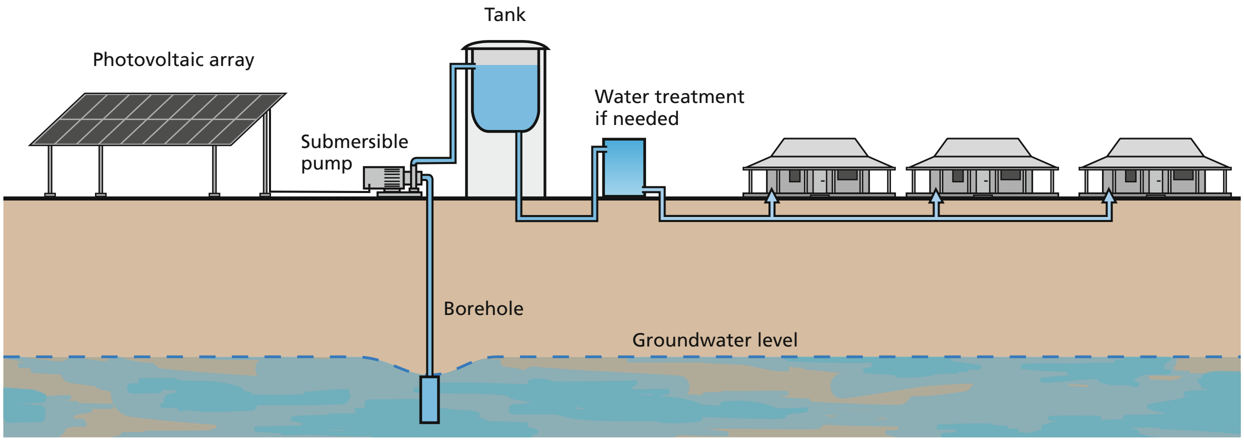
→ References and further reading materials can be found on page $$$

A.13 Solar (Energy source)

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 4, 6, 7, 8, 9	Household/school/ neighborhood/community/ health center	Sometimes	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/m^2 for every month of the year. Identifying the yearly and seasonal sunshine is therefore important to decide whether solar panels are a feasible alternative 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 highly skilled 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 at the level of the capital city
- 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 $$$

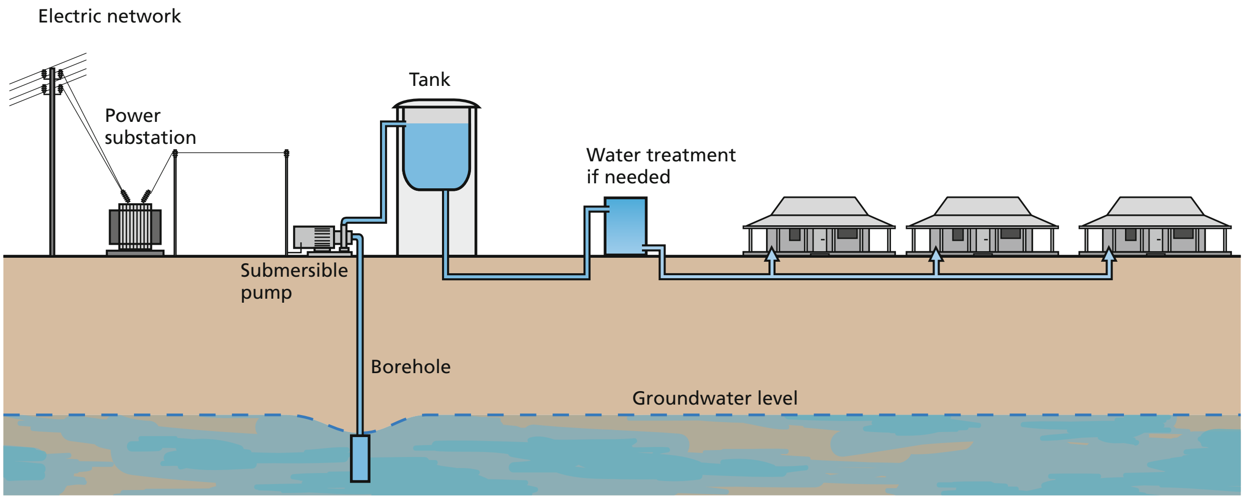
A.14 Electric (Energy source)

Applicable to systems
2, 3, 4, 6, 7, 8, 9

Management level
Community/centralized, technical support required for high-tech components

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 centralized location
- Can be operated simply (but operators must be trained on risks)
- Automation is possible

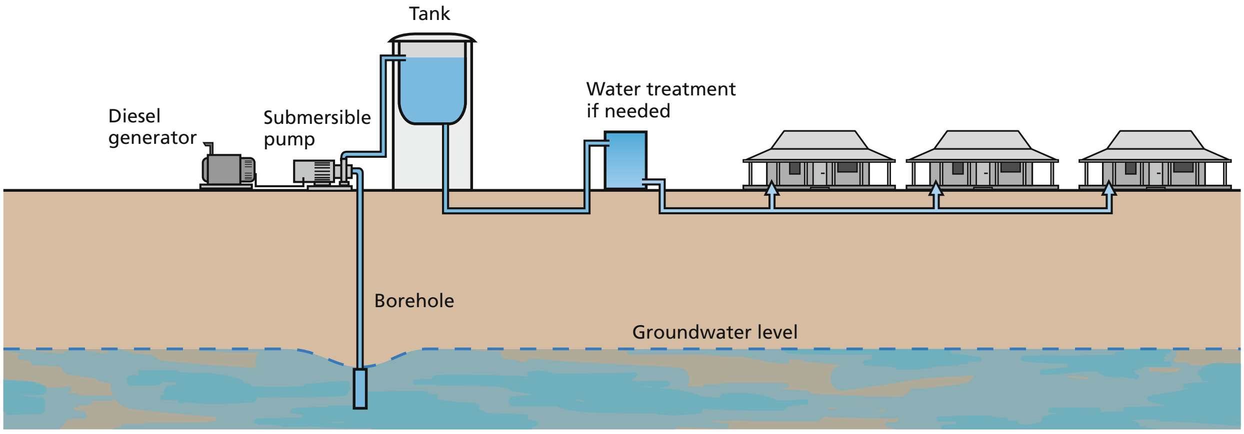
⊖ Disadvantages

- 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 $$$

A.15 Internal combustion engine – diesel and petrol (Energy source)

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 4, 6, 7, 8, 9	Household/school/neighborhood/community/health center; technical support required for high-tech components	Sometimes	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 1,000 kW. The number of cylinders can range from 1 to more than 16 in some cases. Typical engine speeds range from 750 to 2,200 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 5,000–50,000 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 sized such that enough energy can be supplied to run the pump as well as start it, as more power is needed. 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 1,000 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 meters 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 implemented, 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 page $$$

T Treatment

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 removed by the method, though some treatment technologies can be applied to multiple contaminants from different groups.

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

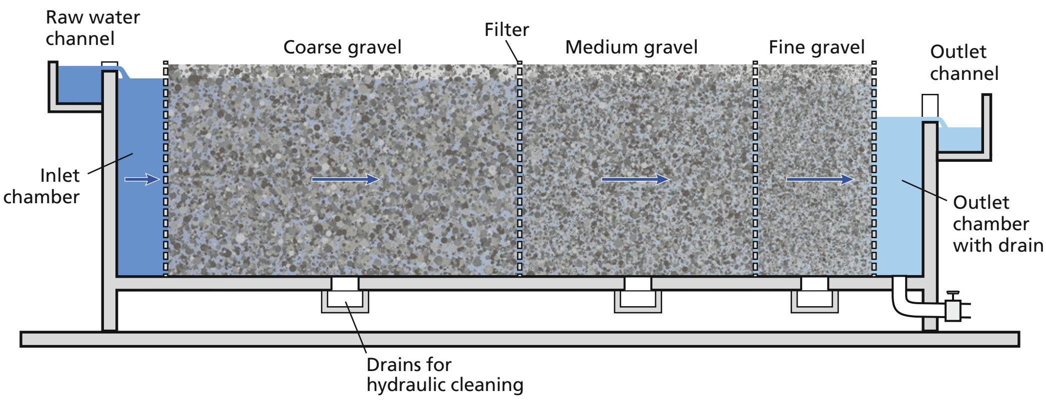
T.5.2 Reverse osmosis

As illustrated in Part 1, a meaningful combination of technologies is often necessary to achieve safe drinking water. The following factors should be considered when choosing a treatment method or combination of methods:

- Availability of water resources 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	Management level	Local availability of technology or components	Technology maturity level
2, 3	Community, centralized	Yes	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 upkeeping the premise around the treatment plant, 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, 2017]), as well as color, 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

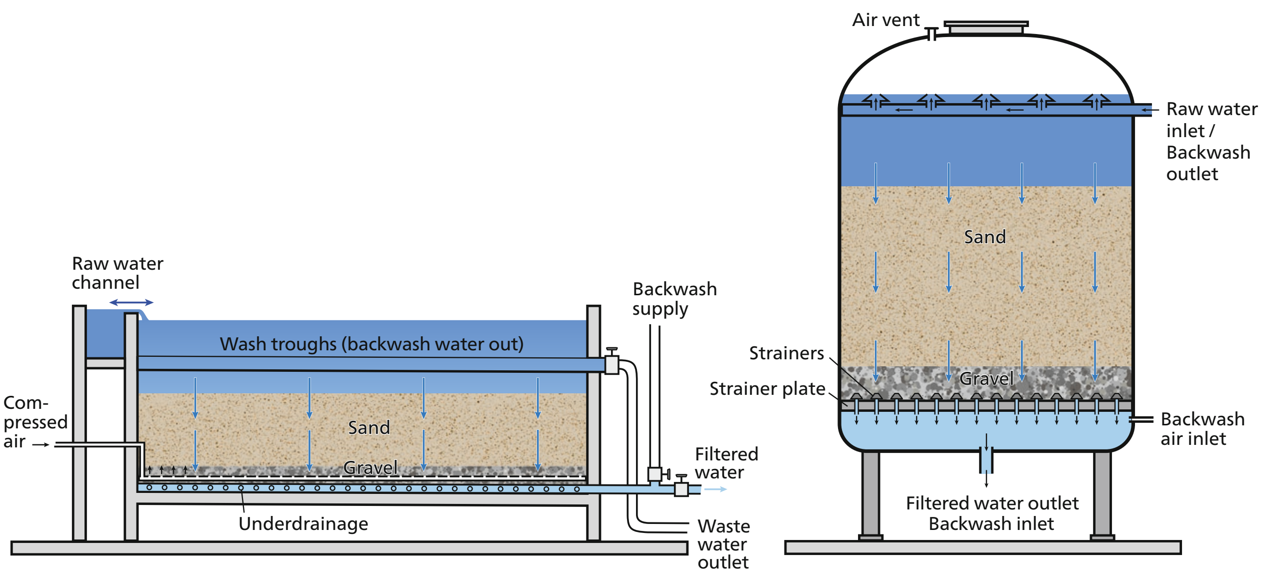
⊖ Disadvantages

- 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 color 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 $$$

T.1.2 Rapid sand filtration

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 7, 8	Community, centralized	Yes	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, UV).

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 color. 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, 2017]).

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 (approx. 0.1 m/h). The respective supernatant water height, corresponding 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 m^3/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 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 highly technical knowhow for operation
- Serves as a biological filter for the removal of organics (if chlorine is not used upstream)

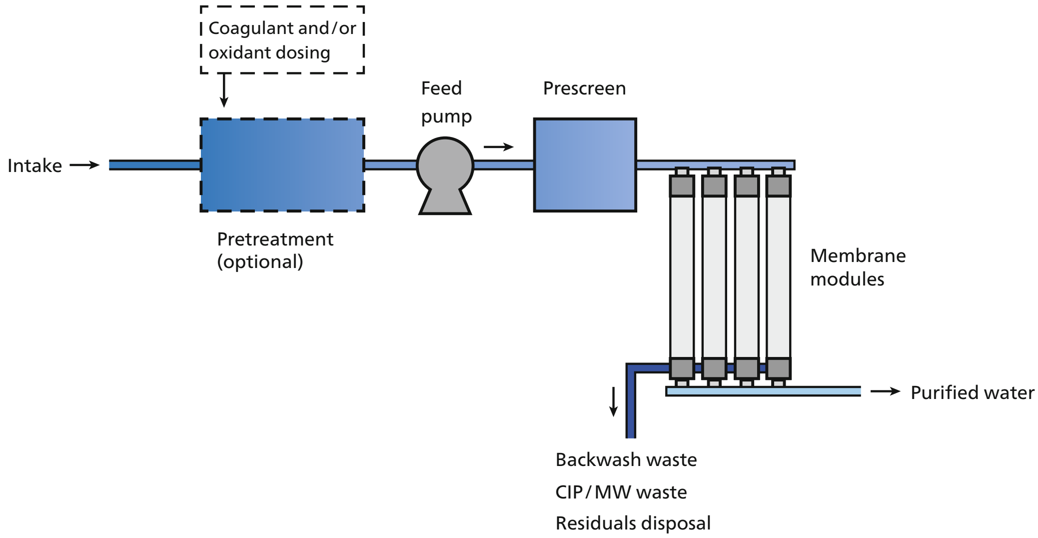
⊖ Disadvantages

- 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 color depending on the operational parameters
- Removes only a limited amount of colloids, organics, and color without upstream coagulation/flocculation/sedimentation

→ References and further reading materials can be found on page $$$

T.1.3 Microfiltration

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 6, 7, 8	Neighborhood, community, centralized	Setting specific, membrane modules may only be regionally available	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, 2017).[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 fouls the membrane. Therefore, MF systems require 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, on-going 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 smaller land area for a treatment plant compared to a conventional filtration systems with transportable and mobile membrane units

⊖ Disadvantages

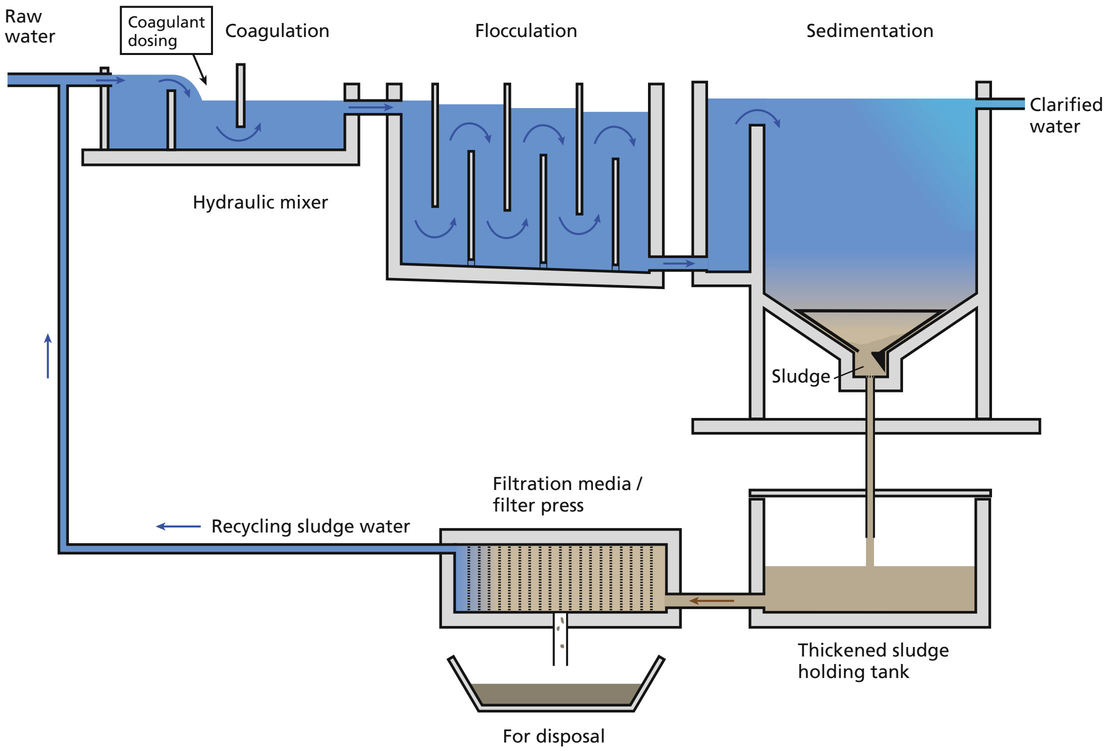
- Has relatively high investment costs and considerable operational and maintenance costs
- Requires skilled personnel for operation and maintenance
- Requires a reliable power supply due to the need for continuous operation to guarantee optimal membrane performance

→ References and further reading materials can be found on page $$$

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 (2017). Potable reuse: guidance for producing safe drinking-water. https://apps.who.int/iris/handle/10665/258715

T.1.4 Coagulation/flocculation/sedimentation

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 7, 8	Community, centralized	Yes	Established technology



Coagulation/flocculation is a pretreatment step to reduce suspended and colloidal solids, organics, and color. 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, 2017]). 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, color, 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 basin[10] 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 meters. In the case of limited land availability, lamella plates[11] 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.[12] 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, color, flow rate). Ideally, monitoring should be carried out online for larger systems (with corresponding exceedance alarms). In smaller systems, grab samples should be analyzed 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. Usually, the produced sludge needs subsequent treatment, degradation, and safe disposal in a landfill or reuse. 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 recycled back 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

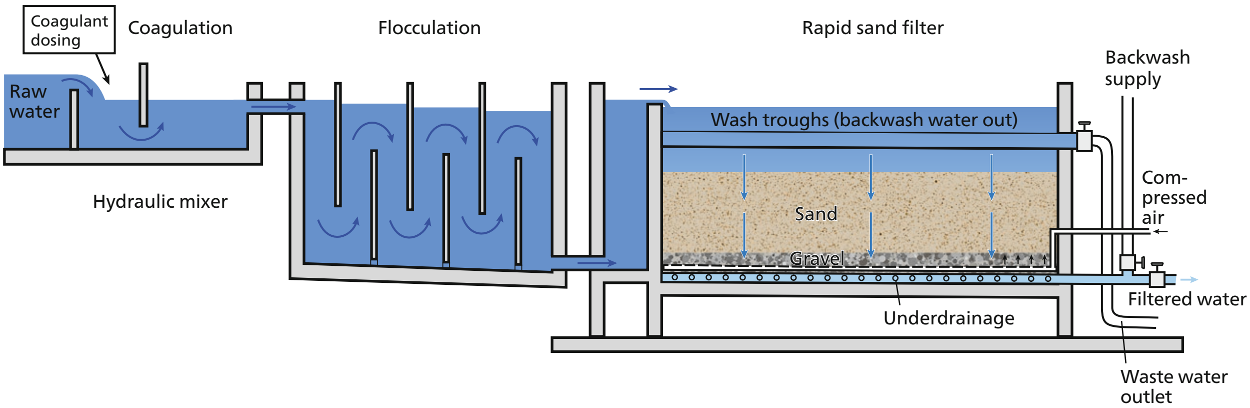
- Requires a lot of land for sedimentation
- Requires skilled operator for raw water quality monitoring, dosage, and chemical handling
- Has poor treatment efficiency in case of under-/overdosage
- Requires continuous supply of coagulant and power for mixing

→ References and further reading materials can be found on page $$$

10 Note - 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.
12 For instructions on how to conduct a jar test, refer to WHO factsheet on *Coagulation flocculation and clarification*: https://www.who.int/water_sanitation_health/hygiene/emergencies/fs2_13.pdf

T.1.5 Coagulation/flocculation/filtration

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 7, 8	Community, centralized	Yes	Established technology



Coagulation/flocculation is a pretreatment step required to reduce suspended and colloidal solids, organics, and color. 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, color, 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 color), 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.[13] This test using the actual raw water 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, color, flow rate). Ideally, monitoring should be carried out online for larger systems (with corresponding exceedance alarms). In smaller systems, grab samples should be analyzed 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, respectively. On-site sludge treatment is described in coagulation/flocculation/sedimentation (see 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 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. Usually, the produced sludge needs subsequent treatment, degradation, and safe disposal in a landfill or reuse. 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 recycled back 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 (T.1.4 Coagulation/flocculation/sedimentation)

⊖ Disadvantages

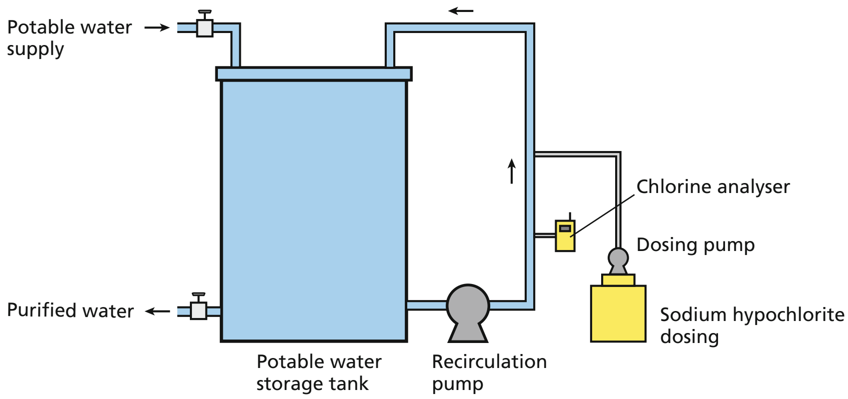
- Requires skilled operator for proper dosage, chemical handling, and filter backwash
- Has poor treatment efficiency in case of under/overdosage

→ References and further reading materials can be found on page $$$

13 For guidance on how to conduct a jar test, refer to WHO factsheet on *Coagulation flocculation and clarification*: https://www.who.int/water_sanitation_health/hygiene/emergencies/fs2_13.pdf

T.2.1 Chlorination

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 6, 7	Household, neighborhood, community, centralized	Yes	Established technology



Chlorination consists of the addition of chlorine compounds to water. Under optimal conditions, chlorine inactivates bacteria and many viruses and provides residual protection that minimizes the risk of microbial re-growth and recontamination.

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 and 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 ($Ca[OCl]_2$), 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. Usually, the dosage ranges from 1–6 mg/L of active chlorine 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 pH < 8. A residual chlorine concentration of ≥ 0.2 mg/L must be maintained throughout the distribution system until the point of delivery to minimize the risk of microbial regrowth/recontamination 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 at: https://www.who.int/water_sanitation_health/water-quality/guidelines/en/watreatpath3.pdf. Chlorine is not effective against protozoan pathogens, such as *Cryptosporidium*, 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 As(III) can be oxidized to As(V), 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 residual chlorine concentration during distribution and storage.

Secondary disinfection: Chlorine is added during distribution/storage within the network via "booster" chlorination stations to ensure an adequate residual concentration is maintained to the point of use. Chlorine disinfection may also be applied at the household level (H.7 Biosand filtration).

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, 2017).

Operation and maintenance

Routine operation includes the dosing of hypochlorite solutions (pre-dissolved $Ca[OCl]_2$ 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 analyzed 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), so that basic 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/odor 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 ensure consumers understand 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)
- Disinfects reliably against bacteria and most viruses if operated optimally

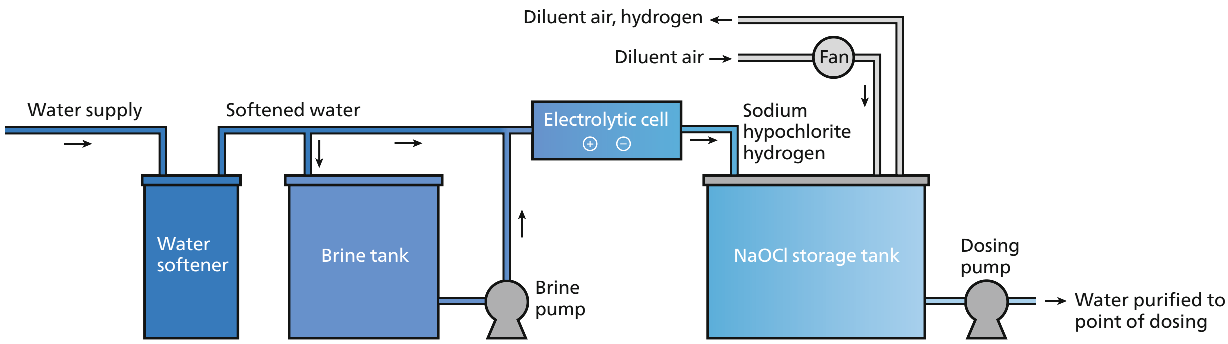
⊖ Disadvantages

- Ineffective against *Cryptosporidium* oocysts (requiring additional barriers for protection
- Requires trained operator and equipment
- Requires higher doses in turbid water (insufficiently pre-treated water)
- Requires regular inspection/replacement due to equipment corrosion
- Water tastes/smells of chlorine
- Deteriorates over time and when stored improperly

→ References and further reading materials can be found on page $$$

T.2.2 On-site electrochlorination

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 6, 7	Household, neighborhood, community	No	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. Usually, the dosage ranges from 1–6 mg/L of active chlorine 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 % 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 the conventional chlorine gas systems, and part of the equipment can be retrofitted to reduce costs. While installation costs are considerably higher, the operational costs and efforts related to assuring the security of chlorine gas transport and storage are considerably lower compared to chlorine gas. Once the 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 hydrogen trapping in the pipes. As for other chlorination techniques, the acceptance of chlorine in previously unchlorinated areas might be limited.

⊕ Advantages

- Functions automatically to a high degree and is less labor intensive than liquid or solid hypochlorite
- Reduces risk from handling and storage of hazardous materials
- Reduces dependency on chemical supplies, their availability, transportation, and costs

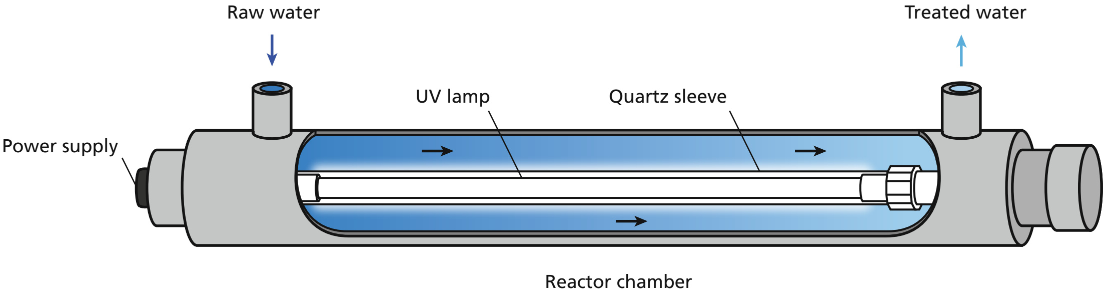
⊖ Disadvantages

- 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

→ References and further reading materials can be found on page $$$

T.2.3 Ultraviolet (UV) light disinfection

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 6, 7	Household, neighborhood, community, centralized	Setting specific, key parts may only be regionally available	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 tubes 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 ≥ 40 mJ/cm². A typical low dose (1–10 mJ/cm²) 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, 2017]). To inactivate bacterial spores and enteric viruses, higher doses (30–150 mJ/cm²) 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 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 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 assure proper disinfection. The nominal lifetime ranges from 8,000–12,000 operational hours (about 1 year of continuous operation) for mercury lamps. For LEDs, the life span 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 assure 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/or residual chlorine) 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 odor of the water
- Does not form disinfection by-products
- Disinfects microorganisms with high chlorine-resistance, such as *Cryptosporidium parvum* oocysts

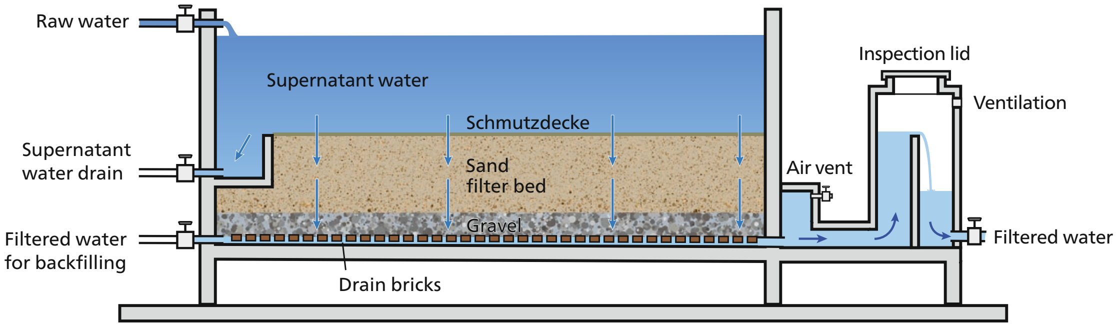
⊖ Disadvantages

- Requires reliable power supply
- Requires spare parts (mercury lamp)
- Does not remove chemical contamination
- Lacks residual disinfectant (safe distribution and storage must be assured)
- Requires pretreatment for turbid and low transmittance waters to increase UV transmittance

→ References and further reading materials can be found on page $$$

T.2.4 Slow sand filtration

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 6, 7	Community, centralized	Yes	Established technology



Slow sand filters (SSF) 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. SSF 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, slow sand filters can achieve up to 6 log reduction value (LRV) for bacteria, 4 LRV 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, 2017).

Slow sand filters are typically used for higher quality surface water sources (turbidity < 10 NTU) 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 like T.2.1 Chlorination may be required as a post-treatment step where there is a risk of later microbial contamination and to provide residual chlorine 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 slow sand filters 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.

Slow sand filters 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, usually it is 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 m^2 filtration area) to municipal water treatment plants.

Operation and maintenance

After running for several months, the SSF 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, wherein 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.

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 ensure that consumers understand the health benefits of drinking SSF-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)
- Does not require skilled personnel for operation and maintenance (however, it has to be conducted thoroughly)
- Can have long lifespan (> 10 years)
- Improves biological stability of water

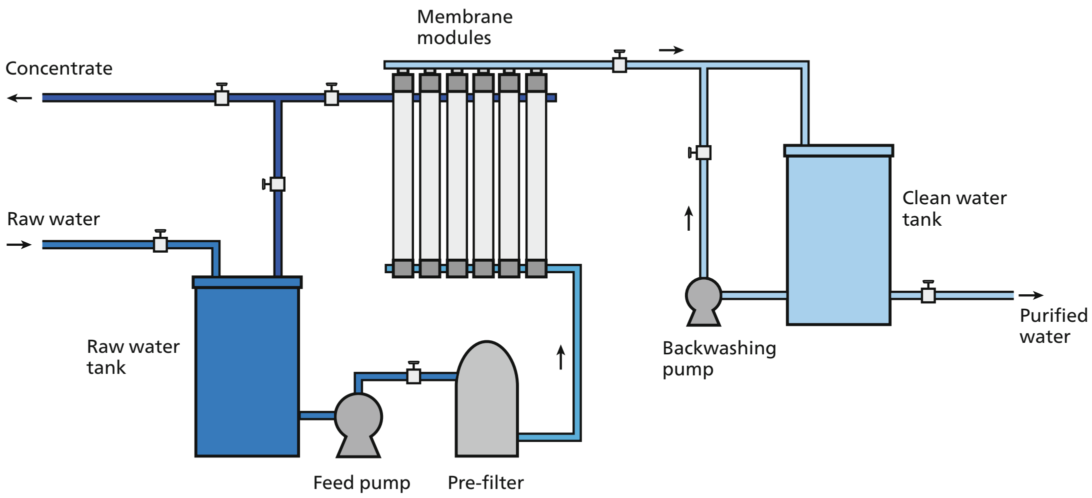
⊖ Disadvantages

- Requires large area
- Requires good raw water; can be clogged easily by mal-operation, 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)
- Requires safe distribution and storage or the addition of chlorine post treatment; no residual disinfection
- May require community engagement/awareness raising on the health benefits of drinking SSF-treated water
- Does not remove inorganic chemical pollutants
- Requires time for ripening and the development of the Schmutzdecke to establish the biological activity and increase treatment efficiency

→ References and further reading materials can be found on page $$$

T.2.5 Ultrafiltration

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 6, 7	Community, centralized	Setting specific, membrane modules may only be regionally available	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 to the needs.

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 ("grow-through") degradation, and general operation and maintenance conditions (WHO, 2017). 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 microfiltration at the same operational pressure, which is usually about 0.5–5 bar. The permeability of standard UF membranes varies between 400–1,000 L/h/m^2/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 manpower and personal protective equipment.

⊕ Advantages

- Removes turbidity effectively
- Provides a barrier to bacteria, viruses (has to be verified), and protozoan cysts
- Reduces organics and color
- Operates constantly and reliably through automation
- Treats water of variable quality
- Uses a smaller land area for a treatment plant with transportable and mobile membrane units in comparison with conventional filtration systems

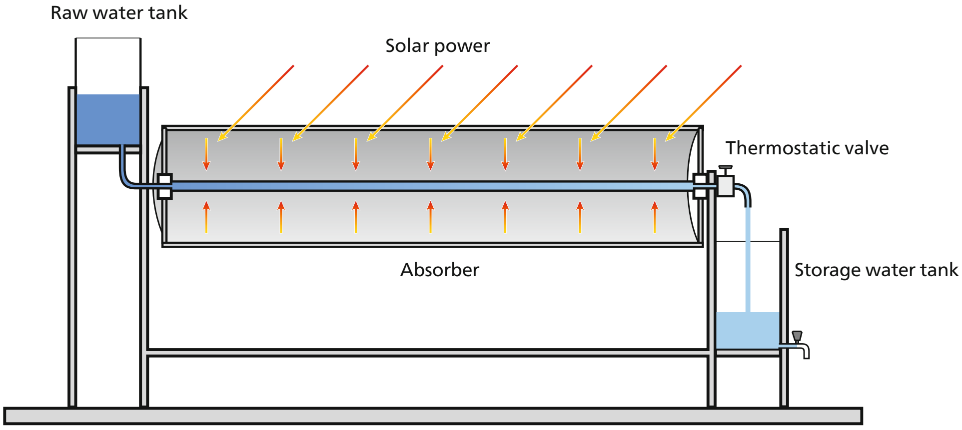
⊖ Disadvantages

- 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 have residual disinfectant (safe distribution and storage must be otherwise assured)

→ References and further reading materials can be found on page $$$

T.2.6 Pasteurization

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 3, 6, 7	Neighborhood, community	Setting specific, some key parts may only be regionally available	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, of >6 log reduction value (LRV) 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 liters 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/or residual chlorine) 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 or chilling the water 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 for different energy sources
- Does not form disinfection by-products

⊖ Disadvantages

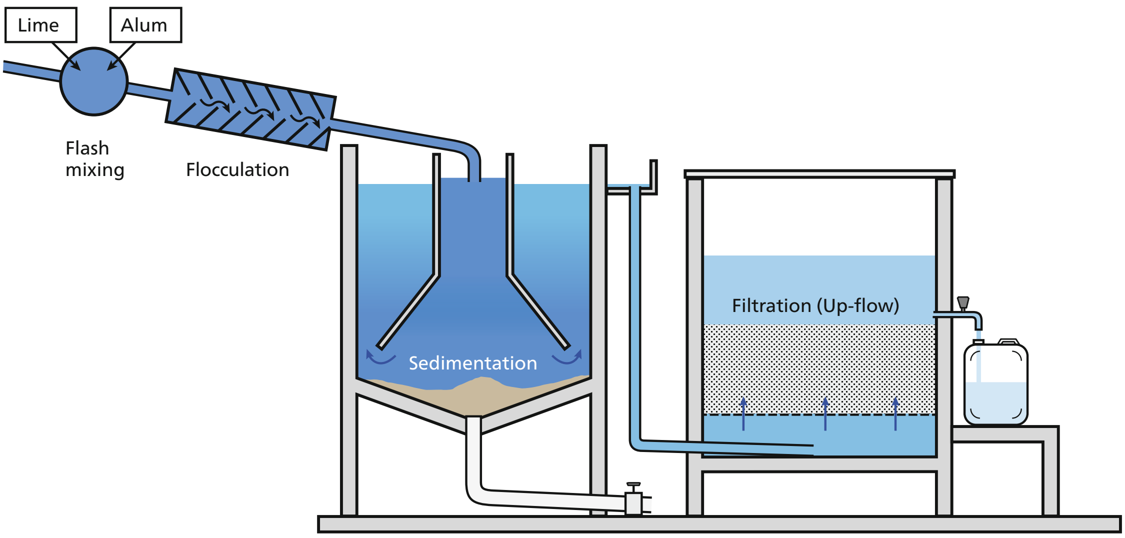
- Has a limited treatment capacity and is rather useful for small-scale systems
- Provides unpleasant, warm water after treatment until cooled
- Is vulnerable to unstable weather (if solar powered); clouds, rain, and polar regions limit efficiency
- Requires safe distribution and storage due to lack of residual disinfection
- Does not remove turbidity, chemical pollutants, taste, and color
- Requires pre-clarification for poorer quality water

→ References and further reading materials can be found on page $$$

T.3.1 Fluoride removal methods

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
6	Community, centralized	Yes, in most settings	Established technology

NALGONDA TECHNOLOGY APPLIED ON COMMUNITY SCALE



Fluoride is a groundwater contaminant from geogenic sources, such as minerals in rocks and soils.[14] 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. This guideline value is set by the World Health Organization for fluoride in drinking water is 1.5 mg/L (WHO, 2017). 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 (namely, dental and skeletal fluorosis, respectively). To counter this, the removal of fluoride from groundwater is possible at household level (see H.9 Solar water disinfection), 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 maintenance 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/overdosing.

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. When required (e.g. after between 3–5 regeneration cycles), however, it involves regenerating the contact bed using alkalis and acids, which are chemicals that need to be stored and handled carefully, so this tends to be easier to do at a 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
- Operates inexpensively

⊖ 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

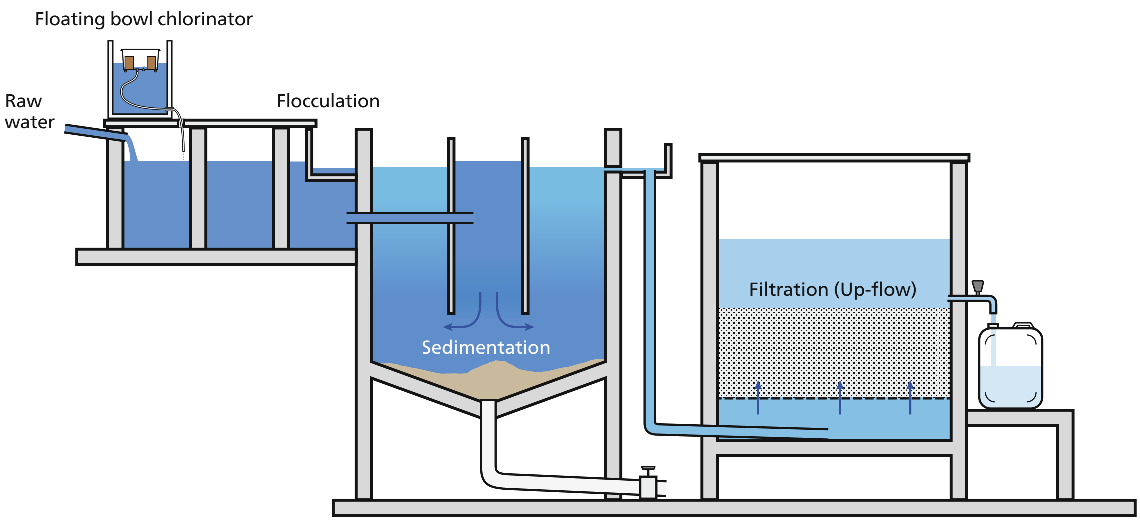
→ References and further reading materials can be found on page $$$

14 See risk maps showing regions with a high likelihood of elevated fluoride contents in groundwater: https://www.gapmaps.org/Home/Public

T.3.2 Arsenic removal methods

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
6	Community, centralized	Yes, in most settings	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,[15] 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 World Health Organization has established a provisional guideline value for arsenic in drinking water at 10 µg/L, which is provisional on the basis of treatment performance and analytical achievability. 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 a household level (see H.10 Fluoride removal filters) as well as on a 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 (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 easier to do at a 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
- Is inexpensive
- Uses chemicals that are often locally available

⊖ Disadvantages
- Requires pre-oxidation
- Generates toxic sludge
- Requires time consuming operation and maintenance

Iron-based solids:

⊕ Advantages
- Removes arsenic efficiently for pentavalent arsenic [As(V)] and to a lesser but initially acceptable level for trivalent arsenic [As(III)]; pre-oxidation is preferred for long operation times.
- 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
- Suffers from interference from sulfate and total dissolved solids (competing ions)

Membrane systems (i.e. reverse osmosis):

⊕ Advantages
- Removes other chemical contaminants and pathogens

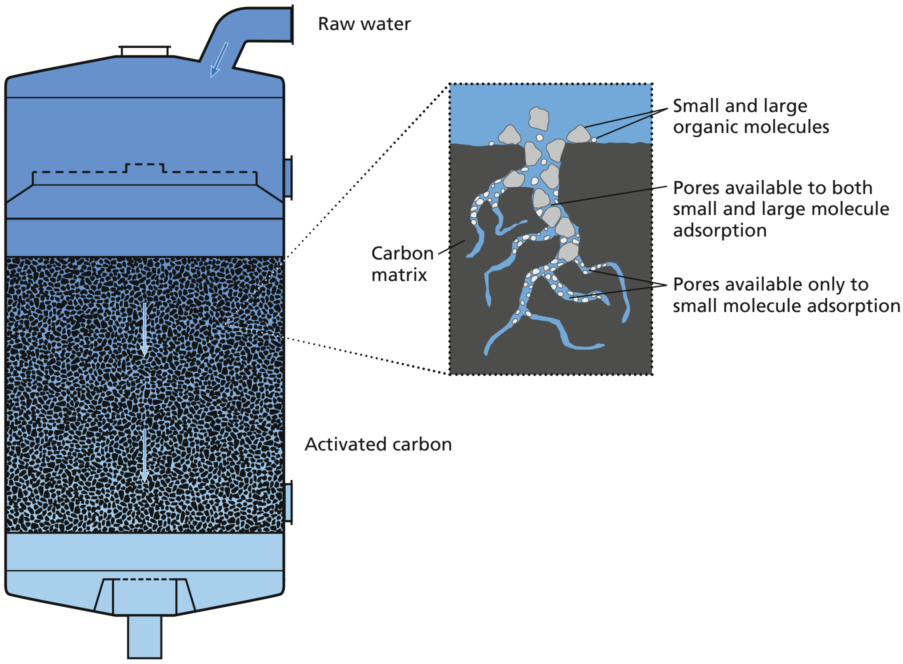
⊖ Disadvantages
- Is complex and maintenance-intensive
- Requires expensive technology

→ References and further reading materials can be found on page $$$

15 See risk maps showing regions with too high arsenic contents in groundwater: https://www.eawag.ch/en/research/humanwelfare/drinkingwater/wrq/risk-maps/

T.4.1 Activated carbon

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
7	Household, community, centralized	Yes	Established technology



Activated carbon (AC) is the most commonly used adsorption method in drinking water to remove taste-, odor-, and color-causing compounds; natural organic matter; disinfection byproducts; 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 can be 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, mostly 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. It 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.

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

Activated carbon 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 odor, chlorine, and organic contaminants
- Is low maintenance
- Adapts to many designs and target compounds
- Filter elements and carbon blocks have simple replacement

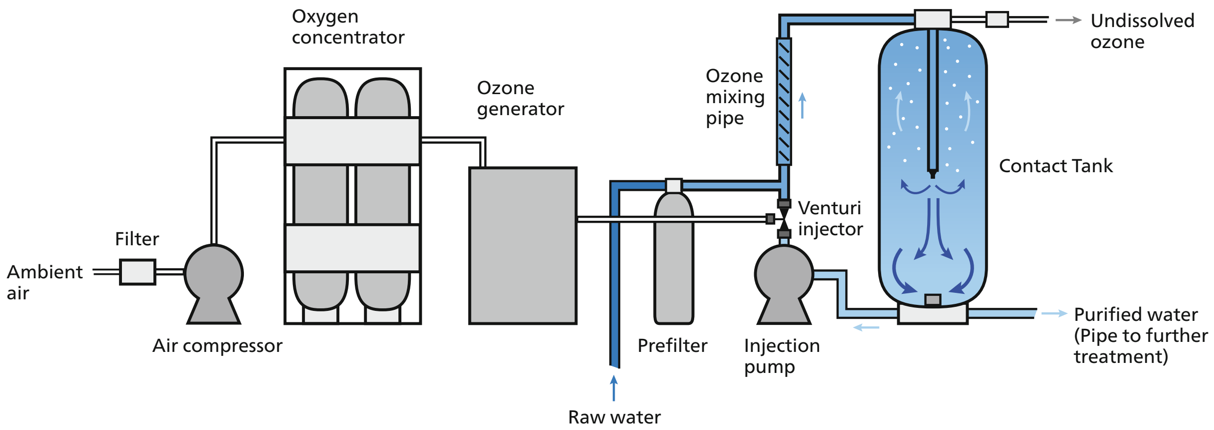
⊖ Disadvantages

- Loses performance rapidly if treating source waters with high turbidity or background organics
- Removes microbial contaminants poorly
- Requires regular replacement of GAC – high costs

→ References and further reading materials can be found on page $$$

T.4.2 Ozonation

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
7	Centralized	Setting specific, some key parts may only be regionally available	Established technology



Ozone gas effectively degrades a wide range of water contaminants, including organic and inorganic compounds, and inactivates bacteria, viruses, and 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 odor-causing compounds). Ozone attacks contaminants either directly or indirectly through its decomposition in water to form hydroxyl radicals (OH-). The OH- 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 color-, taste- and odor-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 subsequent 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 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 here: https://apps.who.int/iris/handle/10665/42796.

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, 2017). 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 irradiation (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.

⊕ Advantages

- Eliminates a wide variety of inorganic (iron, manganese, sulfur) and organic contaminants (micropollutants) as well as color-, taste- and odor-causing compounds
- Effectively inactivates bacteria, viruses, and protozoa over a wide pH range
- Disinfects *C. parvum* oocysts and *G. lambia* cysts
- Ozonation by-products are generally removable by subsequent filtration step

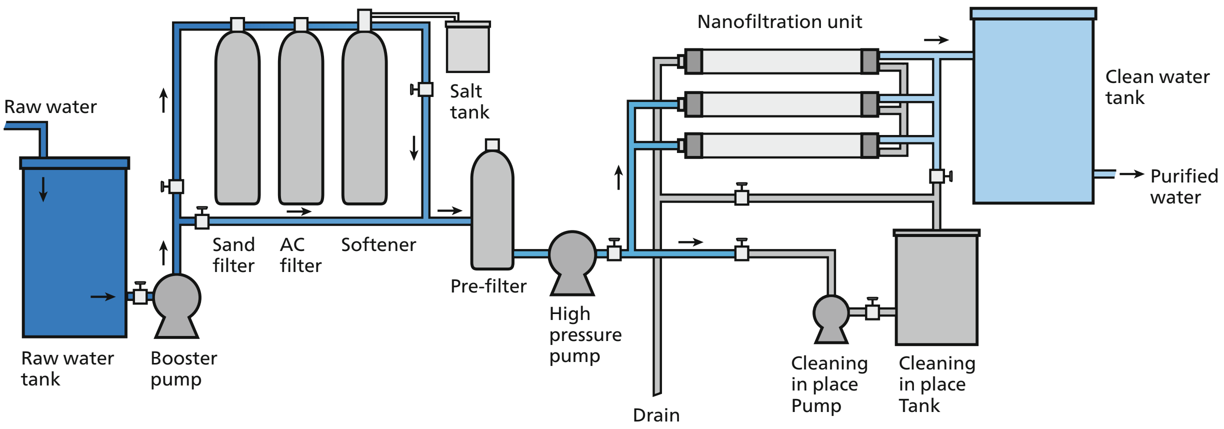
⊖ Disadvantages

- 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 $$$

T.4.3 Nanofiltration

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
7, 8	Community, centralized	Setting specific, membrane modules may only be regionally available	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 did 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 circulated 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 product 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 on-going technical support from the manufacturer (including the possibly 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.

⊕ Advantages

- Produces constant, high-quality water
- Retains organic pollutants fully
- Removes microbial pathogens effectively
- Softens the water
- Operates fully automatically

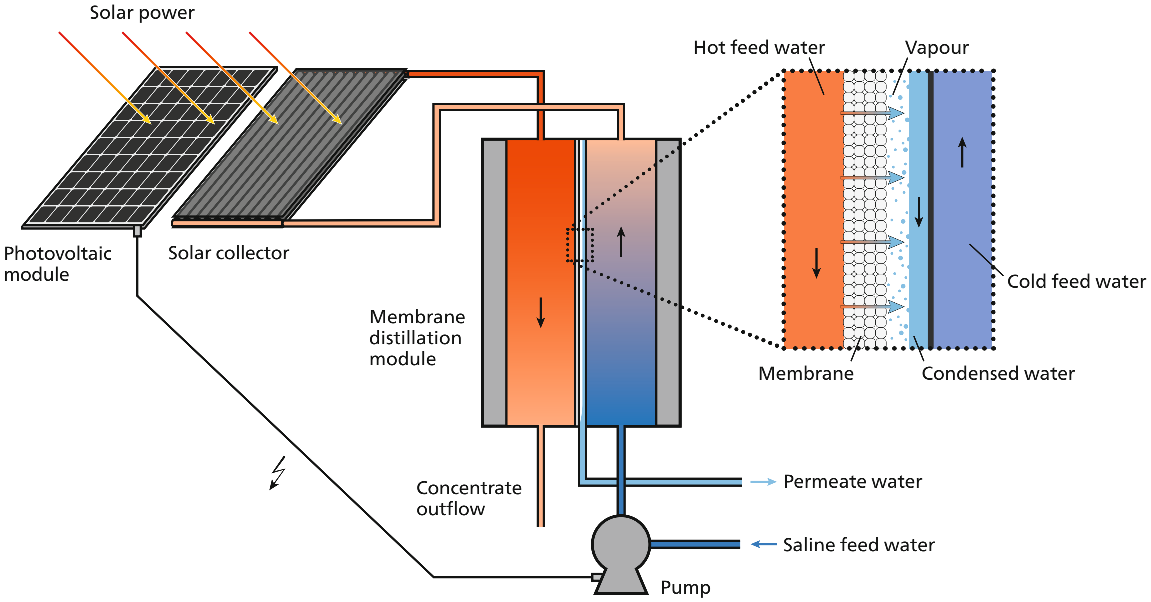
⊖ Disadvantages

- Is a highly complex process
- Produces a concentrate that needs to be discharged or treated separately
- Has high operational and maintenance costs
- Needs on-going technical support from the manufacturer (including on-site assistance)

→ References and further reading materials can be found on page $$$

T.5.1 Membrane distillation

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
8, 9	Community, centralized	No	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/m^3 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.

On-going 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

Remineralization: Membrane distillation might require post-treatment to increase the mineral content or to adjust the pH.

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 due to innovative technology

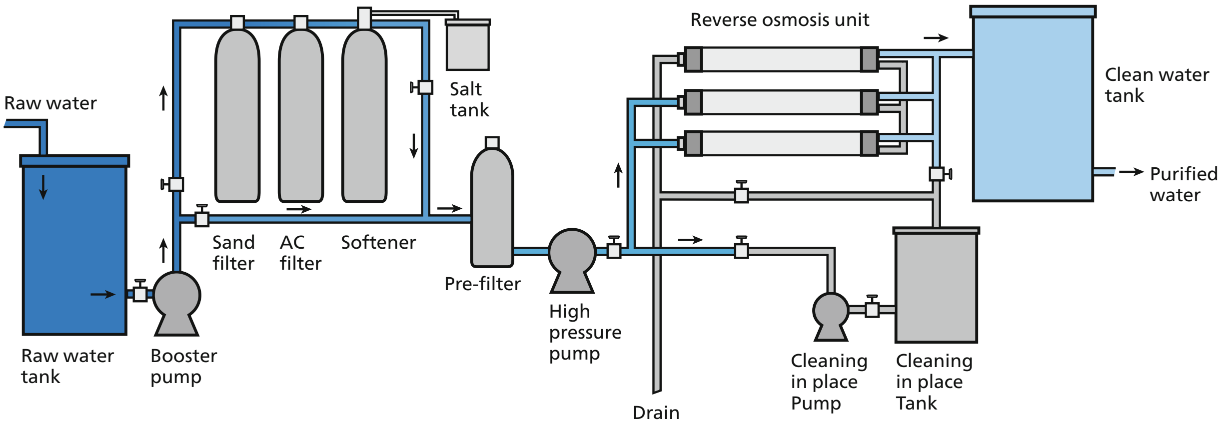
⊖ Disadvantages

- Requires heat source
- Generates reject stream that requires separate handling or diligent discharge
- Has only limited number of companies offering packaged MD units and limited experience
- Needs on-going technical support from the manufacturer (including on-site assistance)

→ References and further reading materials can be found on page $$$

T.5.2 Reverse osmosis

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
7, 8, 9	Community, centralized	Setting specific, membrane modules may only be regionally available	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/m^3 for seawater and 0.4–2.0 kWh/m^3 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 ultrafiltration or multi-media filtration, for example, controls the organic and particle load entering the RO step. Cleaning in place (CIP) allows significant recovery of membrane performance, which tends to deteriorate over time due to aging, 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, but 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, 2017).

Demineralized 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, a post-treatment including the remineralization of desalinated water or blending with other water sources is required.

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 on-going 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 predefined parameters, the maintenance provided by a qualified manufacturer's technical support team or the 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 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.

Remineralization might be required to increase the concentration of calcium and magnesium salts and reduce the risk of corrosion. However, RO-treated water can be consumed without re-mineralization when the lack of minerals can be compensated through other sources, such as through diet.

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 reject stream that requires separate handling or diligent discharge
- Requires experts to be available due to high complexity
- Needs on-going technical support from the manufacturer (including on-site assistance)

→ References and further reading materials can be found on page $$$

D Distribution and transport

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	Management level	Local availability of technology or components	Technology maturity level
4, 5, 6, 7	Household	Yes	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 30 L, with 20 L 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 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 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 tightly and properly sealing filled jerry 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.

⊕ Advantages

- Available almost everywhere and robust
- Very low cost
- Easy to clean
- Usual way of carrying water when distribution systems are lacking
- Available in different volumes

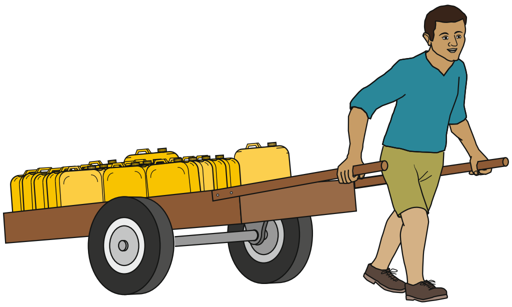
⊖ Disadvantages

- 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
- Water transported by one person (with the typical size jerry can) is likely to be sufficient to cover daily drinking, cooking, food hygiene, handwashing and face washing needs. However, adequate quantities for bathing and laundry are likely not sufficient, nor for handwashing where enhanced hygiene behavior is required, such as during infectious disease outbreaks (WHO, 2020).

→ References and further reading materials can be found on page $$$

D.2 Water vendors (carts and trucks)

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
3, 4, 5, 6, 7	Household, community, neighborhood, decentralized	Yes	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 from door to door to users.

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 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 do have income-generating activities might not have time to carry water on their own or do not want to spend time queuing, meaning they may also rely on water-vendor services. Water vending should be considered an interim solution while adequate distribution systems are put in place.

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 affect the effort that is needed to collect 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.

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), residual chlorine 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 re-contaminated 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, and should be routinely cleaned and disinfected with a chlorine solution. Recontamination can be reduced when jerry cans or other containers are tightly and properly sealed after filling. Water aging and stagnation in containers and tankers can cause taste and odor problems, residual chlorine 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 public utilities and can provide a solution where 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 $$$

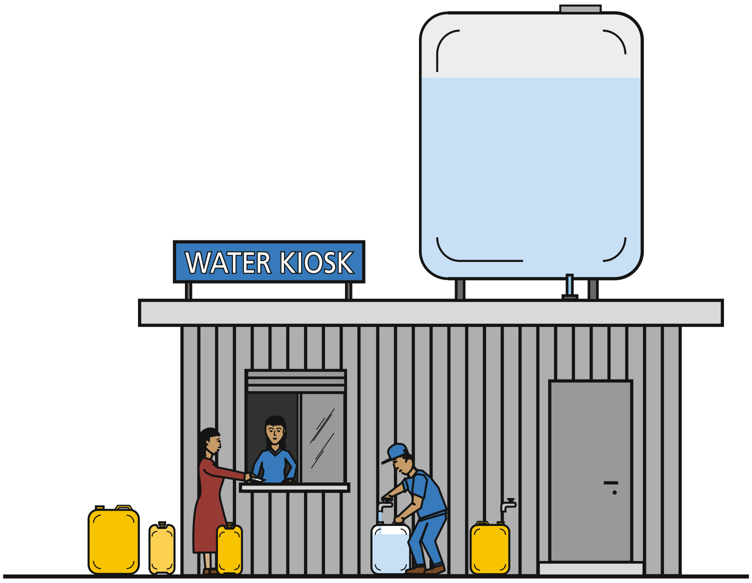
D.3 Water kiosk

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 groundwater, 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 200–3,000 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 less common, though are 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 water treated in the 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 implemented quickly and adapted to local conditions

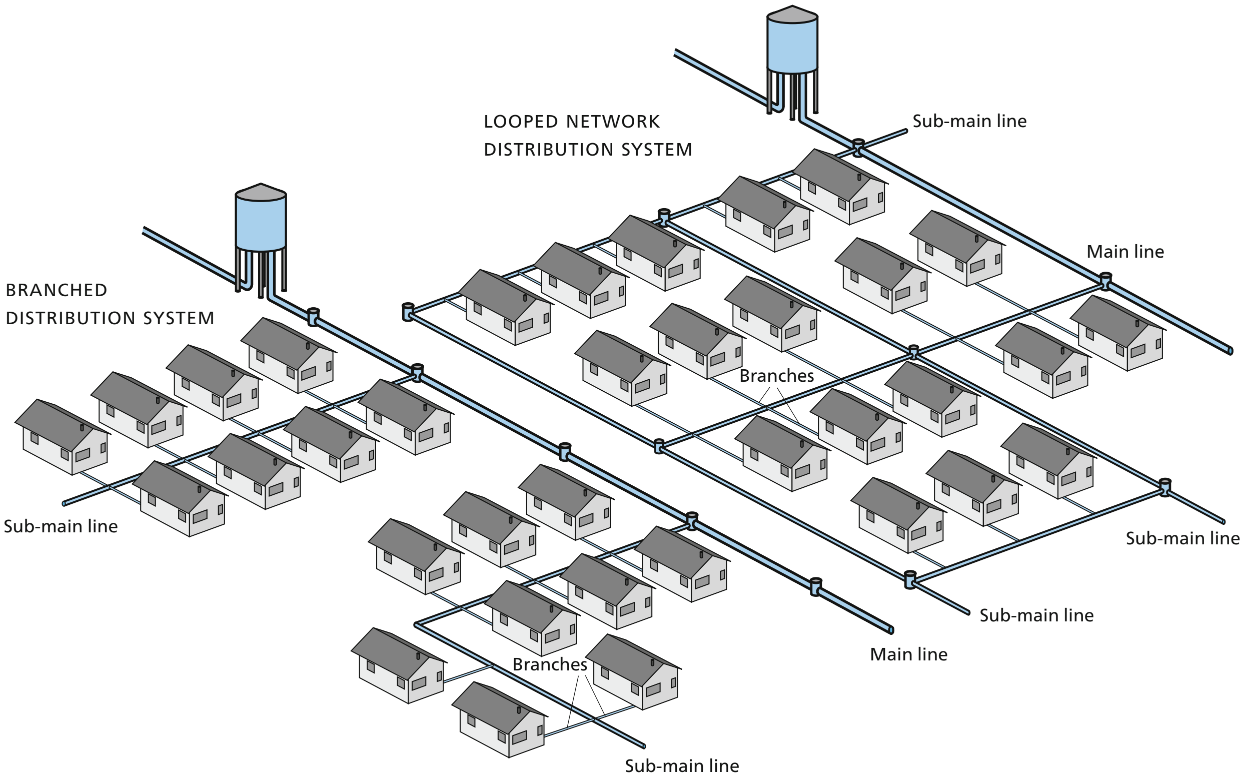
⊖ Disadvantages

- Risk of misuse or poor management of funds
- 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 $$$

D.4 Small public and community distribution system

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
3, 5, 6, 7, 8	Community, neighborhood, decentralized	Yes	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. The pressure of at least 5–10 m of the water column is needed to prevent the ingress of polluted seepage water, protecting the water supply network, and to assure 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 500 m 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 domestic and household needs as well as occasionally for animals and the irrigation of gardens. They are 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 disposal 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, aging, 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.

Bad design of the pipes and structures may cause severe corrosion even when appropriate materials are used. 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 residual chlorine 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 tracks
- During continuous supply, no need for safe water storage or household water treatment

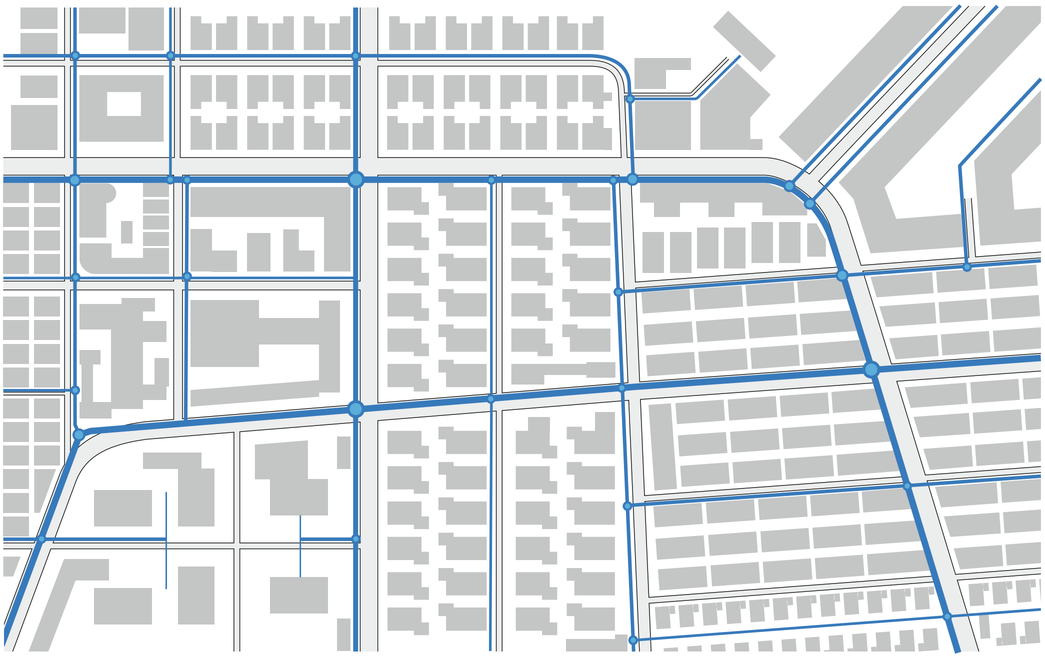
⊖ Disadvantages

- 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 page $$$

D.5 Centralized distribution systems

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
2, 8, 9	Centralized	Yes	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 100–400 L per person per day, including losses due to leakage. It is considerably higher than 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 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, aging, 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. A poor design of the pipes and structures may cause severe corrosion, even when appropriate materials are used. 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 residual chlorine 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.

⊕ 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
- During continuous supply, no need for safe water storage or household water treatment
- Water can be used for multiple purposes

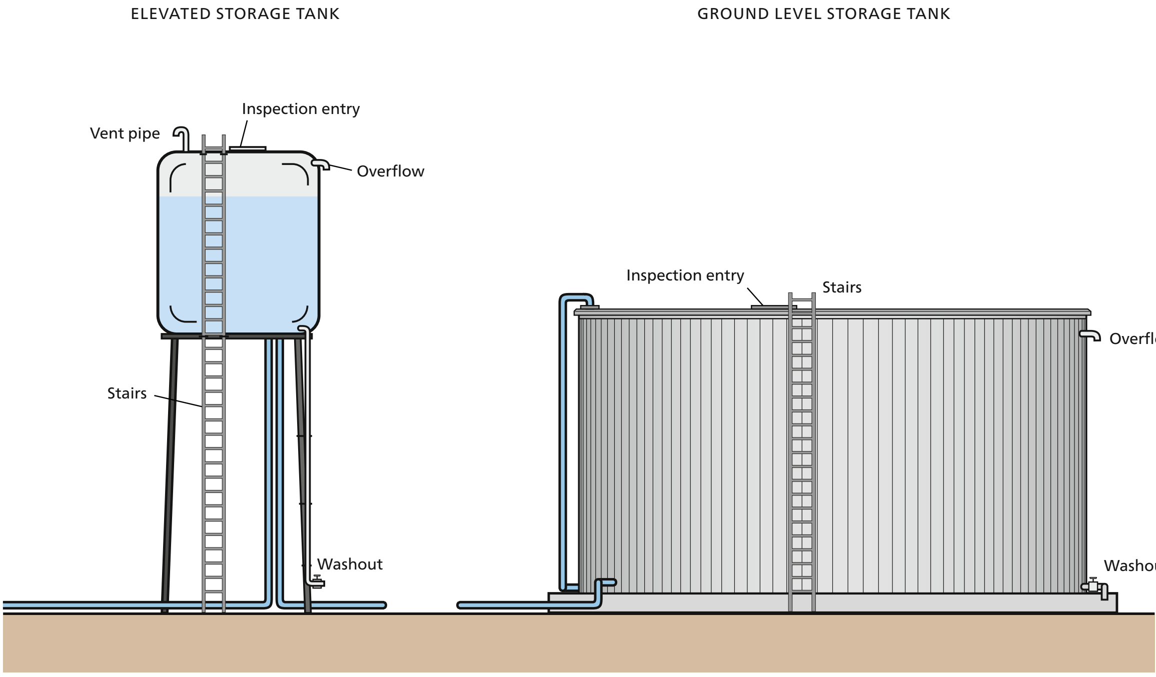
⊖ Disadvantages

- 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 residual chlorine concentrations
- Supply breakdowns and interruptions due to maintenance works or the deterioration of poorly managed infrastructures
- High investment and management costs
- Aging and need for long-term planning to manage aging infrastructure

→ References and further reading materials can be found on page $$$

D.6 Storage tanks or reservoirs

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
1, 2, 3, 5, 6, 7, 8, 9	Community, neighborhood, school/health center, decentralized, centralized	Yes	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 in ground-level, underground or 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 meters 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,[16] which can lead to low-flow zones and issues associated with excessive water age and stagnation (taste/odor, chlorine decay, and microbial regrowth/recontamination) and inadequate contact time (e.g. where disinfection is practiced). 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 $$$

16 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.

H Household water treatment and safe storage

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 program 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.

Performance classification	Bacteria (log10 reduction required)	Viruses (log10 reduction required)	Protozoa (log10 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

Table 2
WHO performance criteria for HWT technologies[17]

17 Results of Round II of the WHO International Scheme to Evaluate Household Water Treatment, World Health Organization 2019: https://www.who.int/publications/i/item/9789241516037

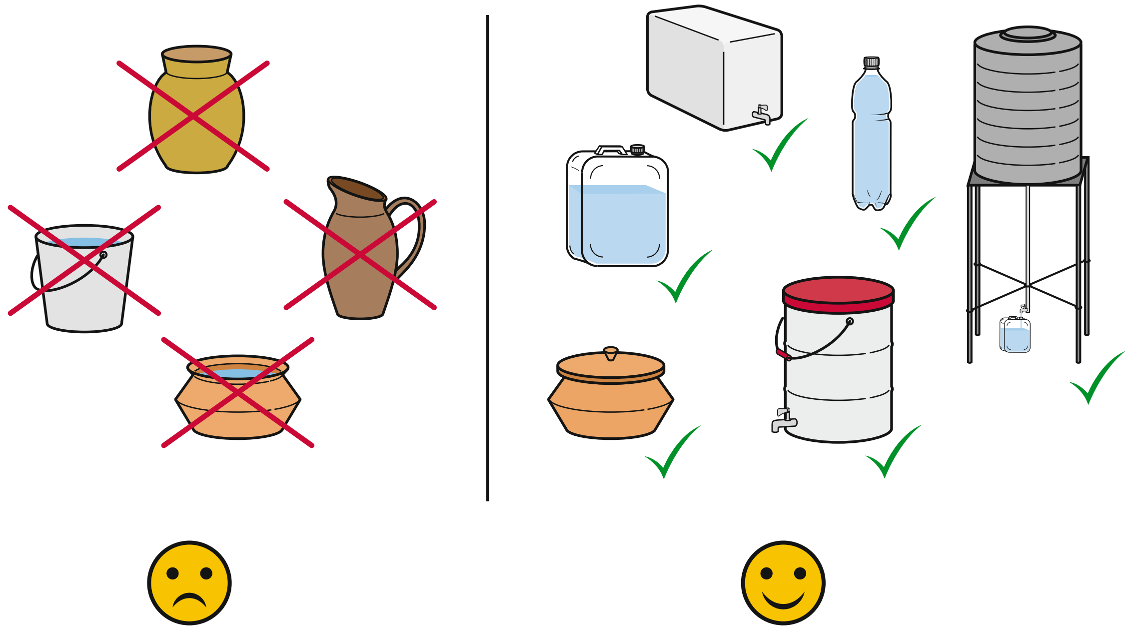
H.1 Storage tanks or reservoirs

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

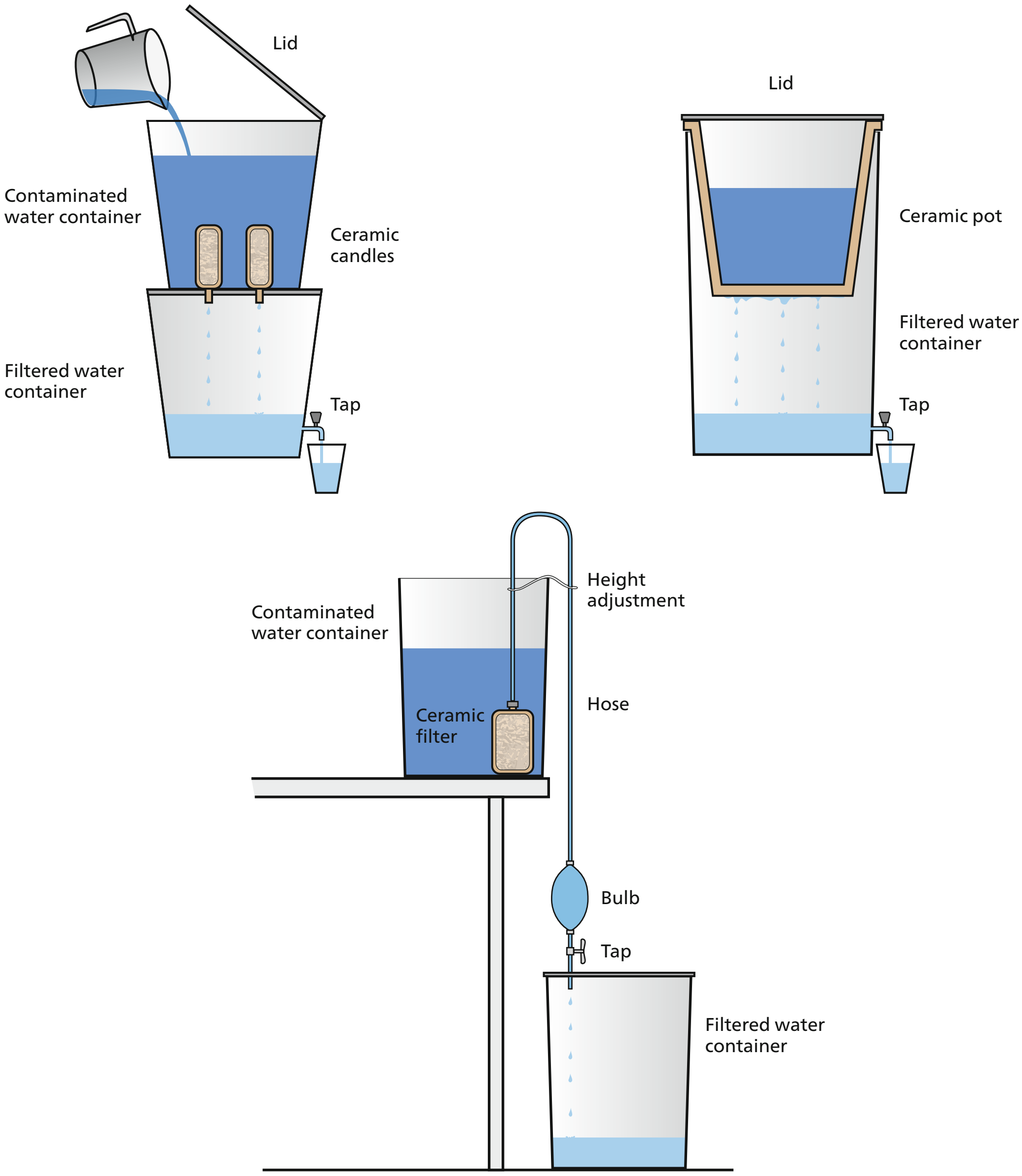
⊖ Disadvantages

- 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 $$$

H.2 Ceramic filtration

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
1, 2, 3, 4, 5, 6, 7	Household	Yes	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 microorganisms.

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, 2021).

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, 2022]).[18] 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 color of the water. Some ceramic candles also contain activated carbon to further improve the taste and odor 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. Pouring boiling water over the candles was shown to be effective in some studies. The candles or pots should not be placed on dirty surfaces 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 compared to other technologies. The treated water storage container and tap may become re-contaminated 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

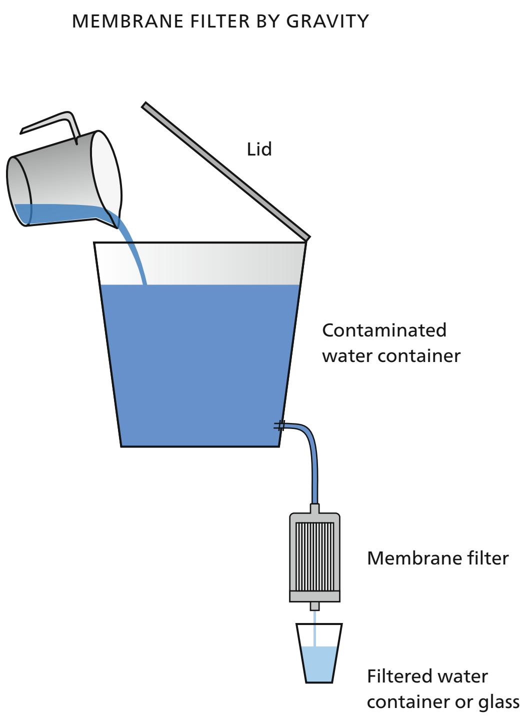
- Limited to no protection from viruses
- Removes bacteria and protozoa to a varying degree depending on the manufacturing quality
- Breaks easily if dropped; cracks are not always visible
- Clogs during filtration of turbid water
- Has relatively short life span (filter candles)
- Provides no residual disinfection
- Has limited affordability

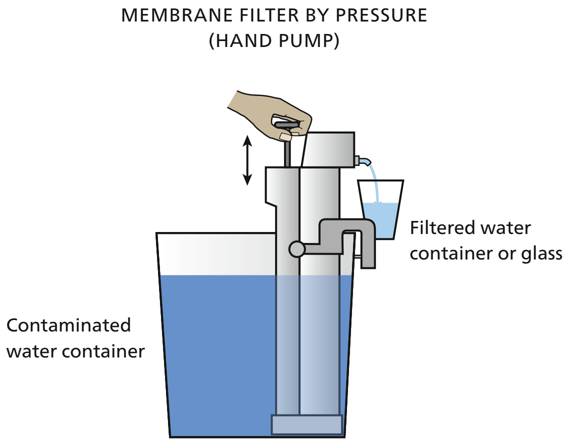
→ References and further reading materials can be found on page $$$

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.3 Ultrafiltration

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
1, 2, 3, 4, 5, 6, 7	Household, school, health center, neighborhood	Sometimes	Established technology





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, 2017]).[18] 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, 2017).[19] Membranes with larger pores (> 40 nm), might show only 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 over 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 odor, 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 assure 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

→ References and further reading materials can be found on page $$$

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.4 Chemical disinfection

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
1, 2, 3, 4, 5, 6, 7	Household, school, health center, neighborhood	Yes	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.[20]

Chlorine effectively inactivates most bacteria under optimal conditions. However, it is less effective against viruses and 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 odor).

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 liters 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 odor. 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 practiced 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.

⊕ Advantages

- Is easy to apply.
- Is cheap and reliable.
- Effectively inactivates most bacteria and viruses
- Provides residual protection for preventing possible recontamination
- Is widely available in different countries

⊖ Disadvantages

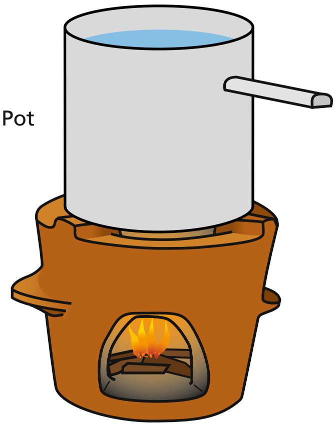
- Must be continuously purchased
- Has unacceptable taste and odor for some users
- Has product-specific dose requirement (depending on product concentration)
- Requires clear water (ideally turbidity < 5 NTU) to be most effective
- Has restricted availability in rural or remote areas
- Not effective against protozoa
- May deteriorate over time and when stored inappropriately

→ References and further reading materials can be found on page $$$

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.5 Boiling

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
1, 2, 3, 4, 5, 6, 7	Household	Yes	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, 2017). 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 contamination.

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 use of safe water storage practices.

Despise 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.

⊕ 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

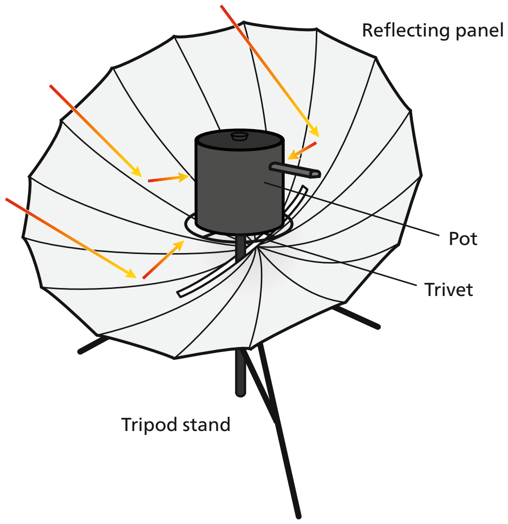
⊖ Disadvantages

- 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 color
- Has no residual disinfection (safe distribution and storage must be assured otherwise)
- Is time consuming
- Requires cooling time before use, except for hot drinks
- Has a risk of burns and injuries

→ References and further reading materials can be found on page $$$

H.6 Pasteurization

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
1, 2, 3, 5, 6, 7	Household, neighborhood	Yes; some key parts may be only regionally available (i.e. thermostatic valve, indicators, etc.)	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 colors. 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.

For vegetative cells of pathogenic bacteria, viruses, and protozoa, > 6 log reduction value (LRV) can be achieved 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) and consumed within a short period of time (max. one day), since microbial re-growth and recontamination can take place.

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 that is not consumed within a short time after boiling should be protected by use of 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
- Has no residual disinfection (safe distribution and storage must be assured otherwise)
- Does not remove turbidity, chemical pollutants, taste and color

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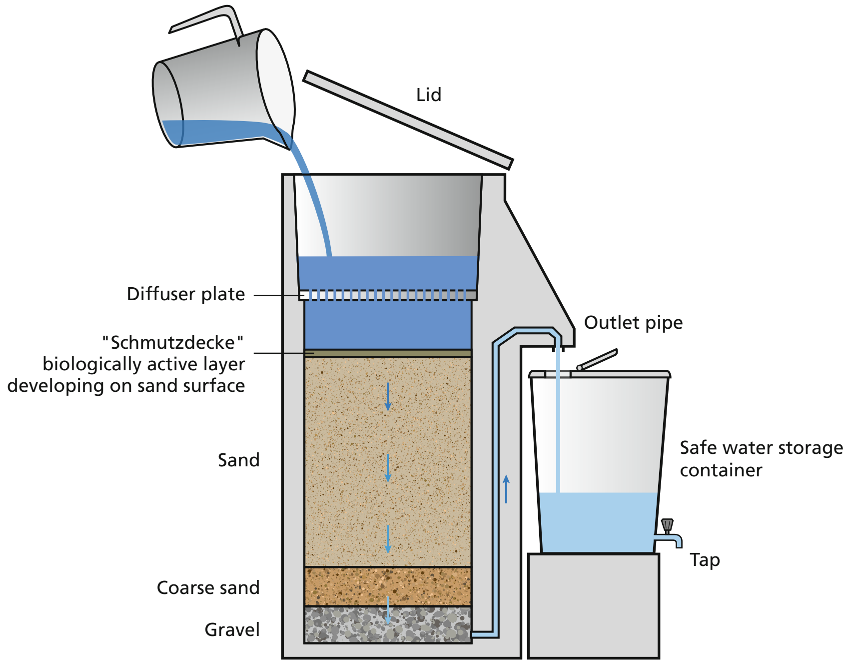
→ References and further reading materials can be found on page $$$

H.7 Biosand filtration

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
1, 2, 3, 4, 5, 6, 7	Household, school, health center, neighborhood, small community	Yes	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 0.9 m high with a surface of 0.3 m^2. 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 directly 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, 2017).[21] 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 when local staff is appropriately trained. 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 from 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 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 opening between the sand grains becomes 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 with the suspended material. The surface water containing the sediment is then removed and 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 color 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 re-contaminated, 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

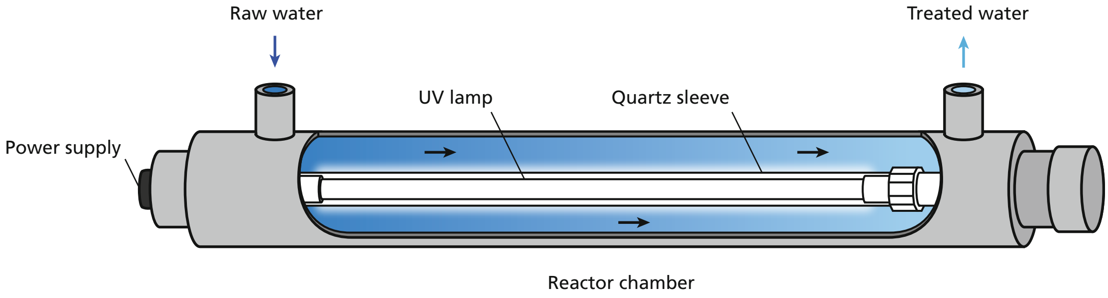
- Lacks residual protection leading to possible recontamination
- The biological layer requires regular use and takes time to develop to maturity (20–30 days). It also loses its efficiency in cold temperatures.
- Has risk of clogging with highly turbid water
- Is difficult to transport and initial cost might be high ($ 25–100 depending on the country and implementing organization)

→ References and further reading materials can be found on page $$$

21 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	Management level	Local availability of technology or components	Technology maturity level
4 (1, 2, 3, 5, 6)	Household, school, health center, neighborhood, small community	Sometimes	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 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 tube 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 tubes. 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 (1–10 mJ/cm^2) achieves at least 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, 2017]).[18] To inactivate enteric viruses and bacterial spores, higher doses (30–150 mJ/cm^2) are required. The UV dose for water disinfection is usually designed for 25–40 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 values.

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 life time 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 should include flushing debris from the reactor and wiping the UV tube or 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 assure 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 assure proper disinfection. For LEDs, the life span 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 odor of the water
- Does not form disinfection by-products
- Disinfects 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

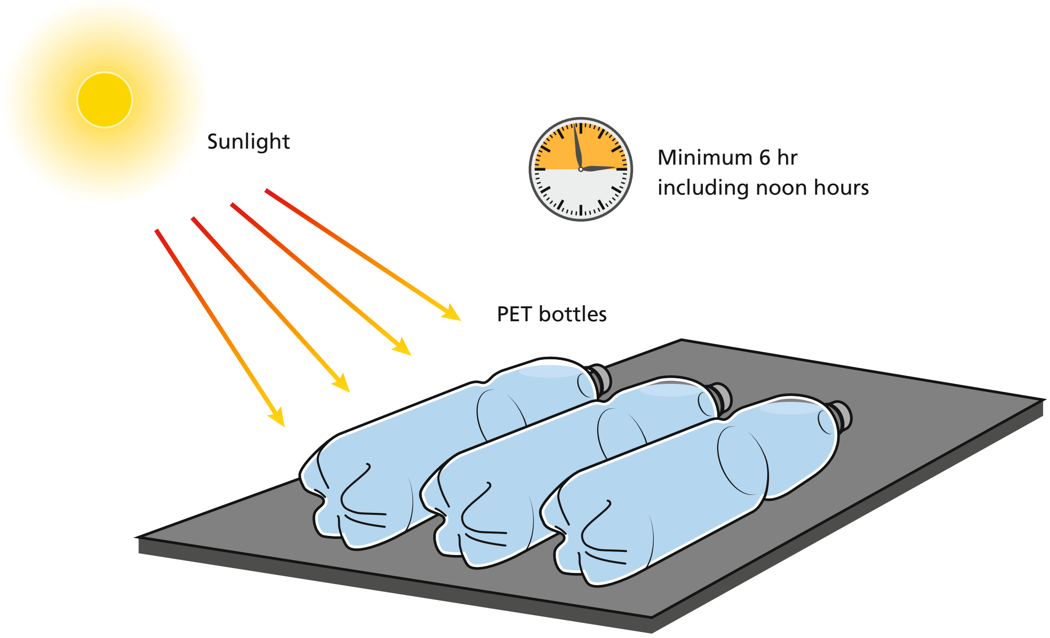
→ References and further reading materials can be found on page $$$

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

22 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	Management level	Local availability of technology or components	Technology maturity level
4 (1, 2, 3, 5, 6)	Household	Yes	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, 2017).[23]

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, a higher turbidity can impact the efficacy of solar disinfection. This high turbidity generally requires pretreatment clarification methods (H.2 Ceramic filtration, H.3 Ultrafiltration, H.7 Biosand filtration) if the water is more than 30 NTU in the case of SODIS.

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 on sunny days, including midday hours, or for 2 days when the sky is more than 50 % clouded. 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 behavior 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 behavioral change process.

After their useful life time, plastic bottles or bags should be collected and send 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 small treatment capacity
- Is vulnerable to unstable weather
- Depends on access to sufficient amount of PET bottles or other suitable containers

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→ References and further reading materials can be found on page $$$

23 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

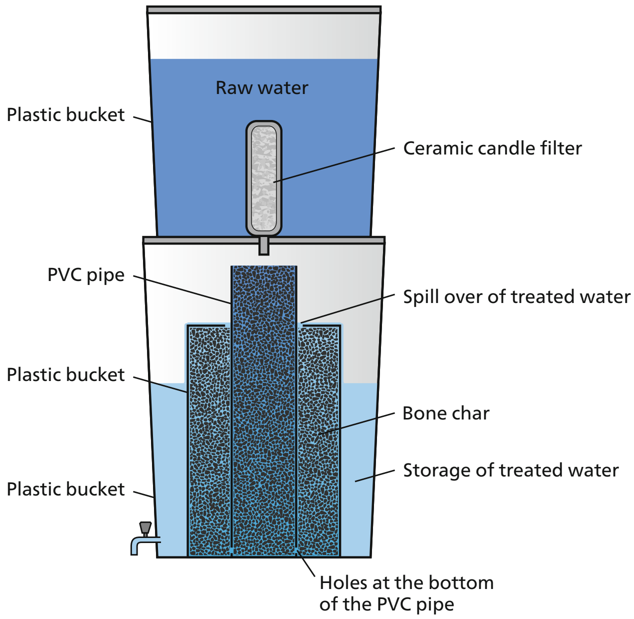
H.10 Fluoride removal filters

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.[24] 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 in some regions is 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 guideline value set by the World Health Organization for fluoride in drinking water is 1.5 mg/L.

Community-scale fluoride removal techniques (see T.3.1 Fluoride removal methods) can usually 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 household 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 analyzed 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 through 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

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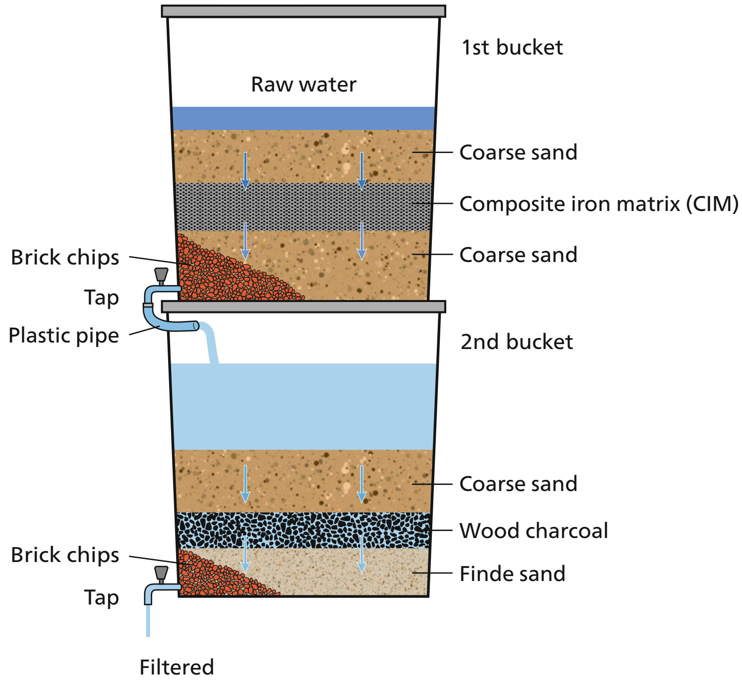
→ References and further reading materials can be found on page $$$

24 See risk maps showing regions with a high likelihood of elevated fluoride contents in groundwater: https://www.gapmaps.org/Home/Public

H.11 Arsenic removal filters

Applicable to systems	Management level	Local availability of technology or components	Technology maturity level
4, 7	Household	Mostly (not always for the adsorption media)	Established technology



Arsenic is a groundwater contaminant originating from geogenic sources, such as the natural minerals present in rocks and soils. 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 guideline value set by the World Health Organization for arsenic in drinking water is set at 10 µg/L. This value is provisional on the basis of treatment performance.

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 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 %. Arsenic household filters are low-cost technologies that are simple to operate and use locally available material and chemicals for the oxidation and coagulation processes.

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 through poor hygiene practices such that 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 filters or in safe water storage containers (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

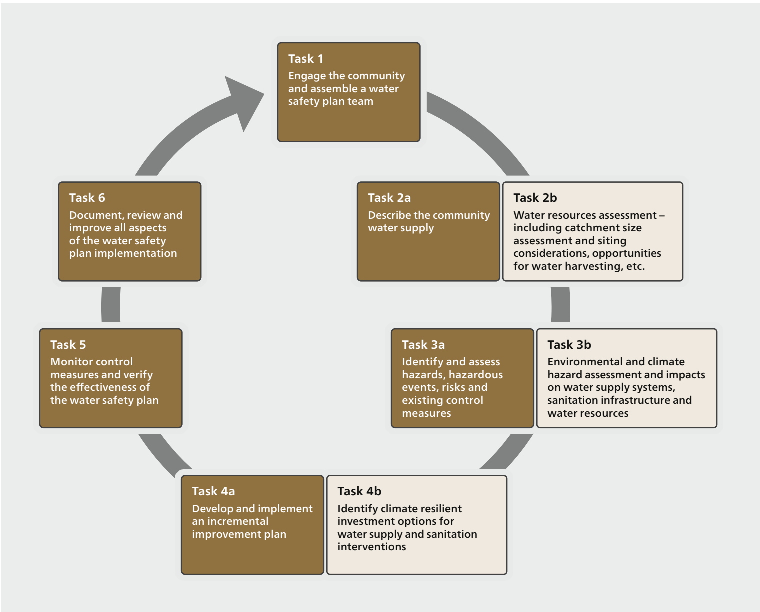
- Is relatively inexpensive and easy to use
- Requires locally available materials

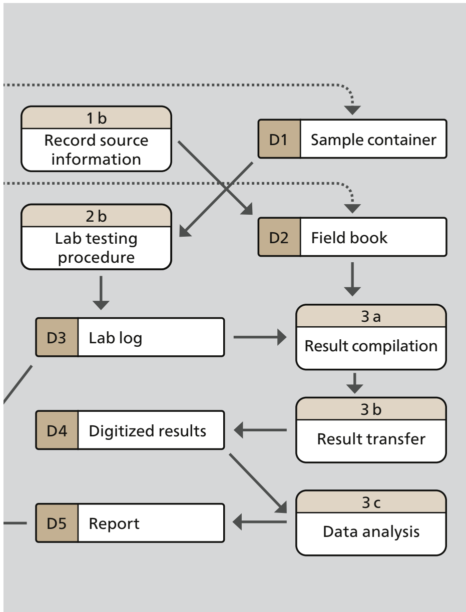
⊖ Disadvantages

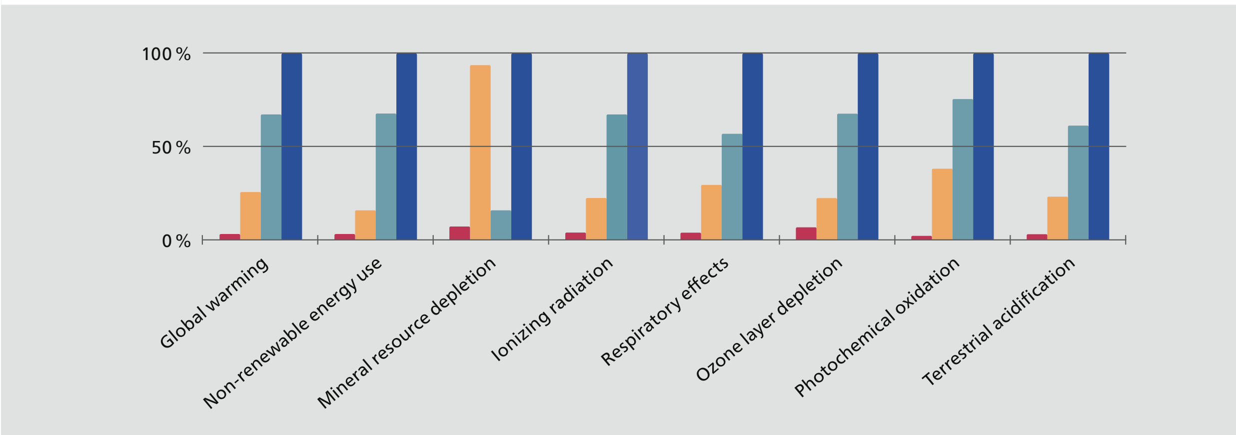
- Has varying arsenic removal efficiencies
- Is not ideal for anion-rich water (e.g. sulphate and phosphate are competing ions)
- Not used regularly by all users

→ References and further reading materials can be found on page $$$

Part 3 | Cross-cutting issues







X 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. 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.

In addition to the topics covered in Part 3, a strong policy and regulatory enabling environment is also important to support sustainable water supply system management. For more information on these considerations, refer to the publications *Guidelines for drinking-water quality* (WHO, 2022) and *Developing drinking-water quality regulations and standards* (WHO, 2018b).

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 self-supply, 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**).

Self-supply

Self-supply is a demand-responsive approach, with water users being responsible for financing and managing their own system. 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, self-supply 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, self-supply 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., 2011). In the United States of America, over 20 % of the rural population relies on self-supply 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 themselves to operate and maintain their own water supply system. This management model typically involves a cost-sharing arrangement whereby an external government agency covers most construction costs and community members then adopt responsibility for the ongoing operation, maintenance, and repair costs. Community members operating and managing the water supply are often untrained or undertrained and sometimes unpaid. 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 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 or "entity" managed water systems are constructed, operated, and maintained 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 by user fees or local taxes. Professional management 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 supporting legal recognition, training and accountability structures), there is increasing recognition of the need to couple community management with robust external support programs (X.11 External support programs), and eventually shift towards greater professionalization of community based-management. 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).

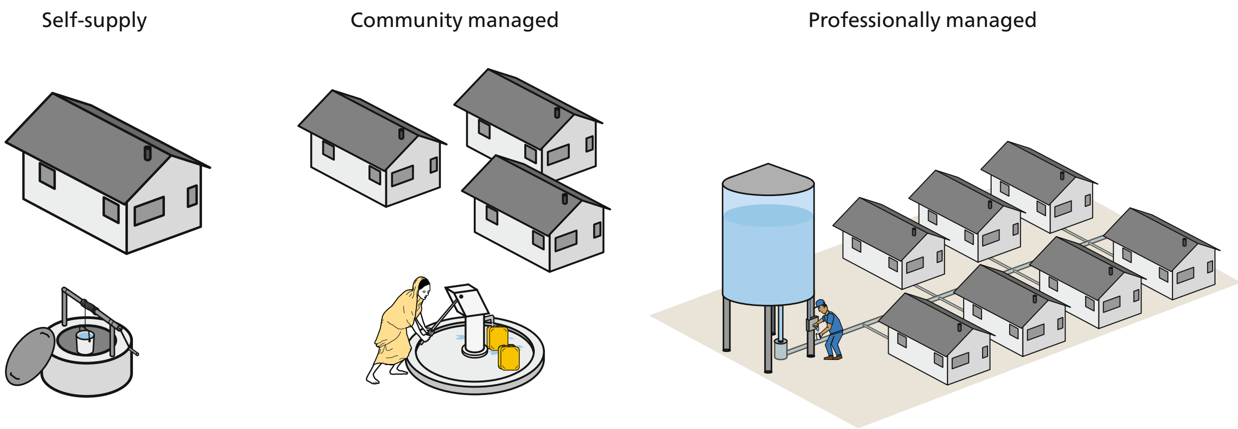


Figure 1

Examples of infrastructure arrangements for three management models: Self-supply with a family well, community management of a 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 socio-economic 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 programs 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 programs 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 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, 2019).

Inclusion: Moving beyond women

Inclusion means more than simply including women. Other social groups that have historically been excluded from participating in water programs include children; people with disabilities or living with chronic illnesses including HIV/AIDS; the elderly; members of specific castes, religions, 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 analyze 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 program 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 1. 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 over-burden 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

Table 1
Activities for gender and social mainstreaming

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 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 analyzed 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 safety)
- 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 CO_2 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.

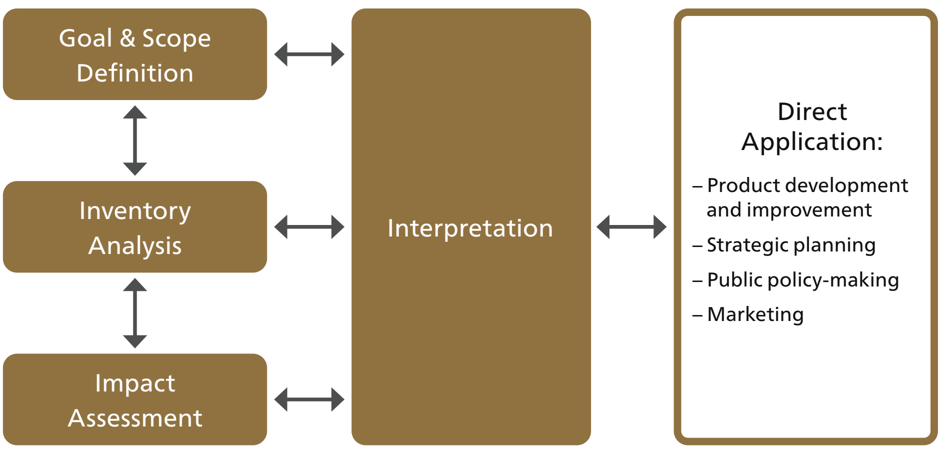


Figure 2
General LCA methodological framework (ISO 14040)

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.

Figure 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 analyzed 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.

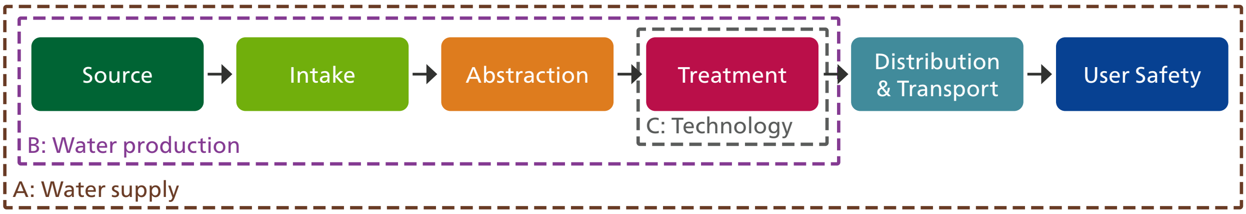


Figure 3
Drinking water LCA system boundaries

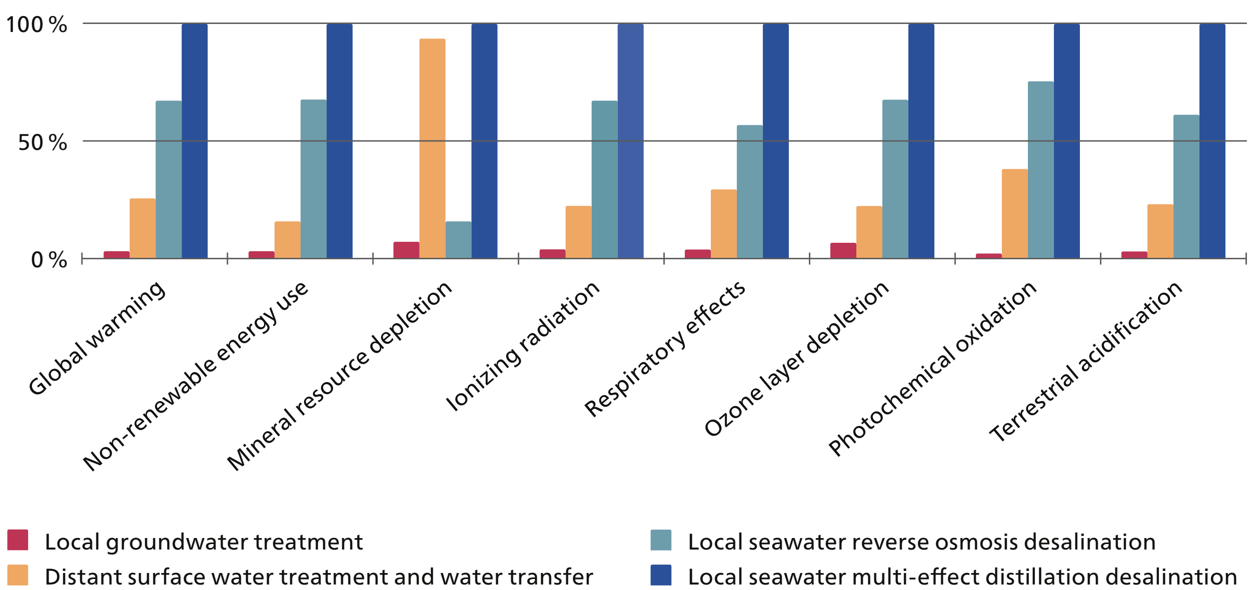


Figure 4
Example of LCIA results on drinking water alternatives (Vince et al., 2008)

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 and in the WHO *Guidelines for drinking-water quality*, is termed water safety plans (WSPs; WHO, 2022).

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, 2022). 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 inspections are a simple risk assessment approach to provide a rapid assessment of potential contamination sources for various water infrastructure arrangements (typically performed using basic sanitary inspection forms; see X.6 Sanitary inspections). 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 inspections 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.

Potential hazards include microbial, chemical, physical, or radiological contaminants, but may also be related to other aspects, such as water quantity and system reliability. 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. Fecal contamination is considered to be the most significant risk to public health associated with drinking-water quality (WHO, 2022). 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 for more details on freshwater systems 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 microbial contamination into the distribution network, while inadequate maintenance and repair activities or backflow in the distribution system may result in recontamination. 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 fecal 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), healthcare (pharmaceuticals, antibiotics), and households (fecal pollution, personal care products). It is impossible and costly to analyze water for all possible contaminants (and their metabolites). 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, 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, and general guidance can also be applied, such as the WHO microbial performance specifications for household water treatment (WHO, 2011b). 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 programs can be implemented by local or national governments, private companies, or non-profit organizations. Supporting programs should include several activities:

- Awareness raising
- Knowledge building (education)
- Stakeholder engagement
- Resource and training availability
- Research to identify adequate measures for addressing risks
- Programs to protect water from contamination

Examples of awareness raising include flyers, healthcare 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 programs 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 cyclic in nature to respond to changes within the system, such as climatic or 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 and incentives for further improvement of the water system.

X.5 Water safety planning

A water safety plan (WSP) is a comprehensive risk assessment and risk management approach that encompasses all steps of the water supply chain, from catchment to consumer. It is a practical and dynamic process that enables the preventative management and monitoring of risks throughout the entire water supply system.

The WHO *Guidelines for drinking-water quality* recommend that all water suppliers apply the principles of water safety planning to ensure the safety of drinking-water supply systems (WHO, 2022). WSPs have been successfully applied at different scales and socioeconomic settings globally (WHO, 2017d). WSPs promote the concept of incremental improvement, i.e. starting simple with stepwise improvements over time, as capacity and resources allow. WSPs enable source protection; contaminant removal during treatment; and prevention of recontamination during distribution, transport, storage, and handling. For a specific water system, each step of the supply chain is scrutinized to identify threats (or hazards/hazardous events) to the water supply system. Risks are assessed and prioritized, and an improvement plan is developed for addressing the identified priority risks. In addition, the WSP must ensure that the effectiveness of all barriers (control measures) is routinely monitored, and that the plan is verified to ensure that it is working effectively. Adequate management and communication strategies should also be in place.

WSP development and implementation

The WSP approach is a flexible, continuous process that should be adapted to the local conditions and circumstances commensurate with the complexity of the system and the available resources and capacity (**Fig. 5**). Key terms used in WSPs are defined in **Figure 6**. A WSP includes the following core components:

- **Preparation:** engaging key stakeholders (including decision makers) and establishing a WSP team with the relevant experience to drive the WSP process.
- **System assessment:** describing the entire water supply system from catchment to consumer to identify threats (hazards/hazardous events) and assess and prioritize the most significant risks.
- **Monitoring:** routine monitoring of barriers (control measures) to ensure they are operating within acceptable limits; applying timely corrective actions where needed (operational monitoring) and verifying the effectiveness of the WSP as a whole through water quality testing, auditing, and surveying consumer satisfaction (verification).
- **Management and communication:** developing standard operating procedures for day-to-day activities and emergency response plans for emergencies as well as developing supporting programs to ensure effective WSP implementation.
- **Feedback and improvement:** conducting routine and as-needed review and revision of the WSP, including following up on incidents and near-misses.

WHO provides detailed guidance tailored for larger systems (e.g. System 2: Centralized surface water treatment; Bartram et al., 2009) as well as for small water supplies (e.g. rural; WHO, 2012b; 2014b). These steps are summarized in **Figure 5**.

WSPs can provide an effective framework to integrate other WASH initiatives that may already be in place, including household water treatment and safe storage, hygiene promotion, and community-led total sanitation. WSPs can also be harmonized with other risk management approaches and the International Organization for Standardization (ISO) risk management guidelines.

WSPs can also be applied as an effective framework for managing the current and future (projected) impacts from climate variability and change, through climate resilient water safety planning (WHO, 2017e) (see X.12 Climate-resilient water supply).

Expected WSP outcomes and impacts

WSP implementation includes intermediate outcomes, such as newly developed or improved standard operating procedures (CDC, 2012), that can positively impact public health. Evaluating the impacts of a WSP requires a broad analysis that goes beyond measuring the direct relationship between water quality and health improvements. The Center for Disease Control proposed a framework for the analysis of four categories of intermediate outcomes: institutional, operational, financial, and policy (CDC, 2012).

Successful implementation of a WSP should result in improvements in the following outcomes (WHO & IWA; Kumpel et al., 2018; Setty and Ferrero, 2021):

- System understanding
- Stakeholder collaboration and knowledge-sharing
- Skills and capacities among managerial and technical staff
- Prioritization of needs
- Infrastructure integrity
- Operation and management practices
- Community confidence in the supply
- Cost efficiencies and revenue generation
- Leveraged financial support

Ultimately, these outcomes are expected to lead to longer-term beneficial impacts, such as improved water quality and quantity, system reliability and service levels, and public health.

WSP Stages	WSP Modules (Bartram et al., 2009)		WSP Tasks (WHO, 2012b)	
Preparation	**Module 1**	Assemble the WSP team	**Task 1**	Engage the community and assemble a WSP team
System Assessment	**Module 2**	Describe the water supply system	**Task 2**	Describe the community water supply
	Module 3	Identify the hazards and hazardous events and assess the risks	**Task 3**	Identify and assess hazards, hazardous events, risks and existing control measures
	Module 4	Determine and validate control measures, reassess and prioritize risks	**Task 4**	Develop and implement an incremental improvement plan
	Module 5	Develop, implement and maintain an improvement plan		
Monitoring	**Module 6**	Define monitoring of control measures	**Task 5**	Monitor control measures and verify the effectiveness of the WSP
	Module 7	Verify the effectiveness of the WSP		
Management and Communication	**Module 8**	Prepare management procedures	**Task 6**	Document, review and improve all aspects of WSP implementation
	Module 9	Develop supporting programmes		
Feedback and Improvement	**Module 10**	Plan and carry out periodic WSP review		
	Module 11	Review the WSP following an incident		

Figure 5
Overview of WSP steps as described in WSP guidance manuals
(Source: adapted from WHO, 2019b)

Sustaining effective WSP implementation

Successful long-term WSP implementation requires WSPs to be viewed as more than a one-off exercise. Rather, WSP integration with ongoing operations, management, and monitoring activities coupled with a regular review underpins effective and sustainable water safety planning.

National top-down WSP directives play an important role in enabling WSP uptake. However, WSP directives alone are not sufficient, unless complemented by genuine supplier support. To achieve this, targeted advocacy plays an important role, communicating the benefits and impacts of WSP uptake to key stakeholders, from operational to management levels.

Surveillance programs (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.

In rural settings, there is also a need to ensure that WSP activities are streamlined and harmonized with related programs from governments and development partners to avoid mixed messaging or resource duplication. This is especially important in settings where there are a number of partners supporting various WASH initiatives.

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).

⊕ **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 unnecessary work
- Inadequate training
- High staff turnover
- Lack of resources (e.g. financial, laboratory)
- Inability to design and carry out audits

Hazard
A chemical, physical, microbial or radiological agent that can cause harm to public health.

Hazardous event
An event or situation that introduces hazards to, or fails to remove them from, the water supply.

Risk
The likelihood that a hazardous event will occur times the severty of its consequences.

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

Control measure
Activities or processes to prevent or eliminate a water safety hazard, or reduce it to an acceptable level.

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

Verification
Confirms if the WSP as a whole is working effectively to deliver safe water.

Compliance monitoring
Confirms if the water quality complies with the regulatory or voluntary drinking-water quality standards.

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

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

Figure 6
Nomenclature for water safety planning (adapted from Bartram et al., 2009)

X.6 Sanitary inspections

Sanitary inspections are a powerful yet simple risk assessment approach widely used in small water-supply settings to identify and manage high-priority risk factors.

Sanitary inspections typically make use of standardized sanitary inspection forms. Sanitary inspection (SI) forms typically consist of a checklist of equally weighted "Yes/No" questions that indicate the presence or absence of observable risk factors (**Fig. 7**). For templates, the WHO (1997) provide SI forms that are widely used globally and can be adapted and tailored to the local context. From these forms, sanitary risk scores are calculated by tallying the number of identified risk factors at different points along a water supply system. This risk score can then be used to prioritize remedial action across systems.

Sanitary inspections are typically completed by individuals with an understanding of public health aspects of water supplies. They are conducted through an onsite visit by an inspector to identify the most basic and common risk factors that may lead to contamination of the water system, such as observable contaminant pathways, actual and potential sources of contamination, and breakdowns in the barriers that prevent contamination (Kelly et al., 2020).

Sanitary inspections provide a low cost, easy-to-use monitoring approach that is particularly suited to small systems and settings with limited resources and/or capacity (Pond et al., 2020). They can be applied to point sources (such as Systems 1, 4, 5, 6, 7) as well as more complex piped systems (such as Systems 2, 3, 8, 9)

Though SI forms are commonly used as a standalone tool for surveillance activities or operational purposes in small supplies, they may also be used to support water safety planning, particularly during system assessment (e.g. supporting hazard identification, identifying existing barriers or control measures, and informing a more systematic risk assessment via risk matrices) and monitoring stages (e.g. supporting WSP verification activities) (see X.5 Water safety planning).

Sanitary inspections and water quality testing

Sanitary inspections and water quality testing can be used in tandem to identify the most important causes of and remedial actions for preventing contamination of drinking water supplies (see X.9 Water quality monitoring). WHO (2017a) recommends water quality testing and sanitary inspections to be undertaken as complementary activities, where possible. To estimate the overall safety of a supply, results from both activities may be combined to indicate the probability of contamination in the future, to inform priority for action. However, due to the dynamic nature of both observable risk factors and water quality (particularly microbial quality as measured by fecal indicator bacteria), SI scores and water 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 water quality testing cannot be performed, sanitary inspections can still provide valuable information in support of effective water supply management.

Importance of customization and training

The questions contained within template SI forms, such as from WHO (2012), may not always be applicable to all contexts. To ensure accurate results, WHO (1997) encourages customizing the content and design of SI forms to suit local contexts where capacity and resources permit. Inspector ability may also affect SI score results, especially where perception of risk is required. Appropriate training of inspectors is important to ensure consistently accurate results (King et al., 2020).

Sanitary inspection (form)

⊕ **Advantages**
- Quick and easy to use
- Results may be used to engage supply owners/operators
- Complements water quality test results, encouraging necessary remedial actions
- Provides a consistent approach to risk assessment
- May support water safety planning activities
- Applicable in a broad range of settings, e.g. from point sources (such as dug wells) to basic piped systems

⊖ **Disadvantages**
- May not capture all relevant risk factors within a system
- "One-off" SIs do not capture the variability in conditions and practices that occur over time
- Accurate interpretation of risk is hampered by inexperienced/untrained inspectors
- Assumes each risk factor carries equal weighting (i.e. equal potential to cause contamination), which may not be the case

Sanitary inspection questions		NO	YES (risk)	What action is needed?
1	**Is the pump damaged or loose at the point of attachment to the cover slab so that contaminants could enter the well?** A damaged or severely corroded pump, or a loose pump that is not securely attached to the cover slab, may allow contaminants to enter the well (e.g. contaminated surface water).	❑	❑	
2	**Is the cover slab absent or inadequate to prevent contaminants entering the well?** The absence of a cover slab, or the presence of a poorly maintained cover slab (e.g. damaged, eroded or with deep cracks), may allow contaminants to enter the well.	❑	❑	
3	**If there is an inspection port, is the lid missing or inadequate to prevent contaminants from entering the well?** A missing, unsealed or unlocked inspection port lid provides a potential route of entry for contaminants to the well (e.g. via contaminated surface water, animals or vandalism).	❑	❑	
4	**Are there any visible deficiencies at any point in the well wall?** Any inadequately sealed points (e.g. gaps, deep cracks, faults) in the aboveground (i.e. headwall) or belowground well wall may result in contaminants entering the well. (Note – if there is no inspection port and a belowground visual inspection of the well is not possible, record this in Section III.)	❑	❑	
5	**Is the apron around the well absent or inadequate to prevent contaminants from entering the well?** A missing apron, or any gaps, deep cracks or faults in an existing apron may allow contaminants to enter the well. For adequate protection, the apron should be at least 1 meter[a] wide all around the headwall, sloping down towards a collar to catch and divert water to a drainage channel.	❑	❑	
6	**Is the drainage inadequate, which may result in stagnant water in the well area?** An absent, damaged or blocked drainage channel, and/or the absence of a downward slope for water to drain away from the well, could result in ponding and stagnated water contaminating the well area.	❑	❑	
7	**Is the fencing or barrier around the well absent or inadequate to prevent animals entering the well area?** If the fencing or barrier around the well is absent, broken or poorly constructed, animals could damage or contaminate the well area.	❑	❑	
8	**Is there sanitation infrastructure within 15 meters[a] of the well?** Sanitation infrastructure (e.g. a latrine pit, septic tank or sewer line) close to groundwater supplies may affect water quality (e.g. by seepage or overflow and subsequent infiltration). You may need to visually check structures to see if they are sanitation-related, in addition to asking residents.	❑	❑	
9	**Is there sanitation infrastructure on higher ground within 30 meters[a] of the well?** Groundwater may flow towards the well from the direction of the sanitation infrastructure. Pollution on higher ground poses a risk, especially in the wet season, as faecal material and other pollutants may flow into the well.	❑	❑	
10	**Can signs of other sources of pollution be seen within 15 meters[a] of the well (e.g. animals, rubbish, human settlement, open defecation, fuel storage)?** Animal or human faeces on the ground close to the well constitute a serious risk to water quality. Presence of other waste (e.g. household, agricultural, industrial etc.) also constitutes a risk to water quality.	❑	❑	
11	**Is there any point of entry to the aquifer that is unprotected within 100 meters[a] of the well?** Any point of entry to the aquifer that is unprotected (e.g. uncapped/open well or borehole) is a direct pathway for contaminants to enter the well.	❑	❑	
	Total number of risks identified:	....	/11	

Figure 7

Example sanitary inspection form and supporting illustration (Source: WHO)

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 inspections 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**):

- 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, 2016). QMRA aids in identifying risks and reducing them below the threshold.

Quantitative estimates used within a 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, 2016).

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 what 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, 2016).

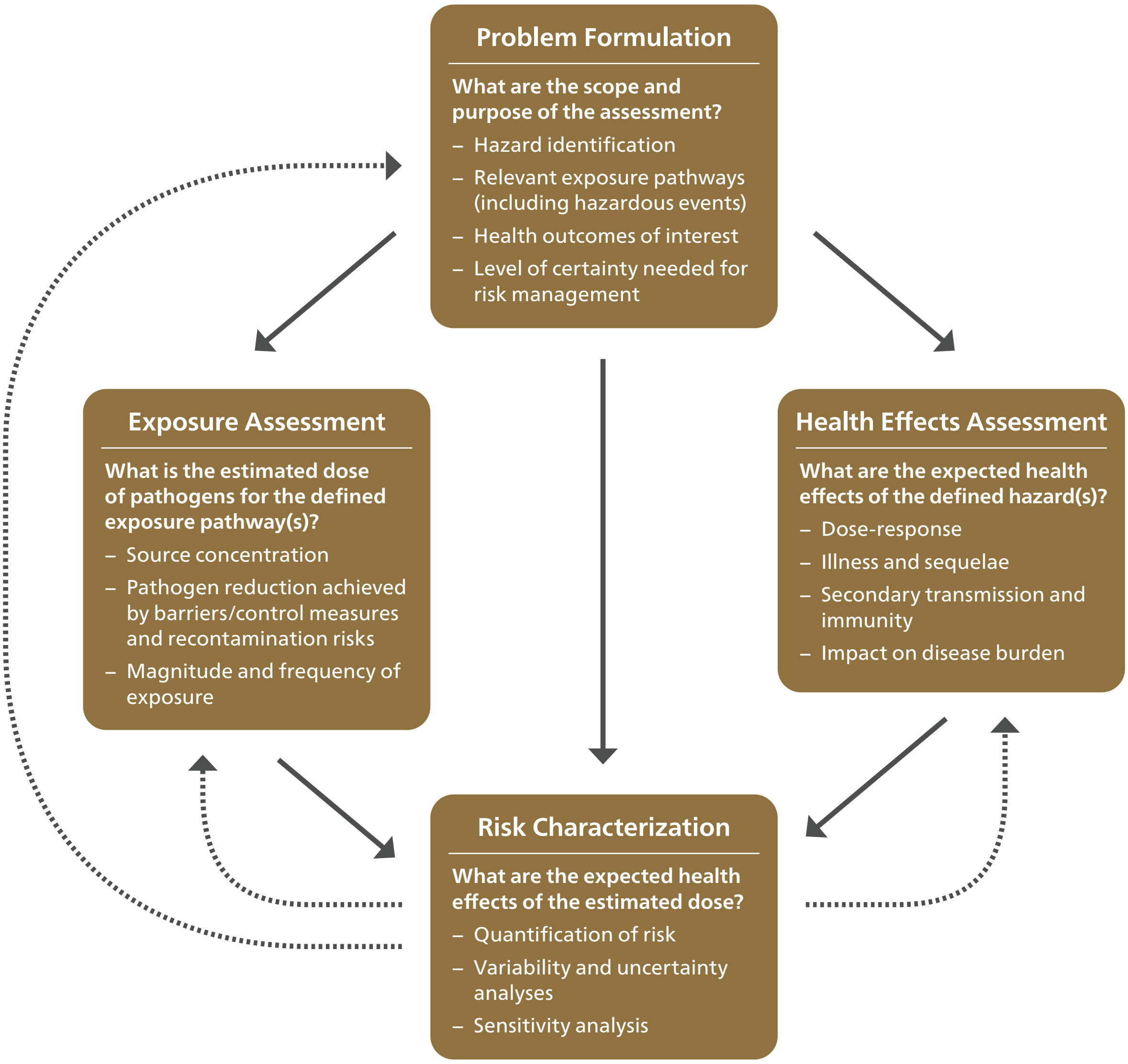


Figure 8

The four interrelated steps of QMRA, adapted from WHO (2016). 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

NEW TEXT WILL FOLLOW 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 and verification (compliance) monitoring, including the target parameters and the agents involved in each approach.

Operational monitoring is routine monitoring performed by water suppliers to determine if control measures are working properly. Verification (compliance) monitoring is monitoring undertaken to assess if drinking-water meets water quality regulatory standards as defined by government agencies, and it may be performed by water suppliers and/or external authorities (e.g. surveillance agencies). For both operational and verification purposes, risk assessment and mitigation approaches, such as those described in the WHO & IWA's *Water Safety Plan (WSP) Manual*, provide a systematic framework for designing site-specific monitoring programs (Bartram et al., 2009). The WSP approach also makes use of monitoring data to inform the reporting, interpretation and corrective actions to be taken.

Operational monitoring

An operational monitoring plan must consider the parameters to target, their monitoring frequency, 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. In remote or rural settings, 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, in addition to reflecting each parameter's variation rate, an effective and sustainable monitoring program will be tailored to local conditions.

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 residual chlorine 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 delivery to users (WHO, 2017a). 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 paraphenylene diamine) indicator test using a comparator. For the dpd test, a tablet reagent added to a water sample changes the color, and the strength of the color change compared to a standard color chart indicates both total and free residual chlorine concentration ranges. Simple test strips are also easy to use and sufficiently accurate for operational purposes.
- **pH** measures the acidity or alkalinity of water. Where chlorine disinfection is practiced, 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 odor 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, 2017d). 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, 2017a).
- **Structural integrity** may be routinely monitored through system inspections, including assessing the adequacy of source protections, structural

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 backflow. 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.

Verification monitoring

The frequencies for verification monitoring are typically based on the population served or the volume of water supplied. More frequent monitoring is required for microbial parameters and less frequent for chemical parameters (WHO, 2022). These indicators include (but are not limited to):

Fecal indicator bacteria such as *Escherichia coli (E. coli)* or thermotolerant (fecal) coliforms are the 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 2). Ideally, test-kits should be appropriately validated before use. For guidance on recommended minimum sample numbers for fecal indicator testing in distribution systems, refer to WHO (2022; Table 4.4).

Chemical and physical contaminants from naturally occurring sources with the most significant health impacts globally are arsenic, fluoride and possibly 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, 2022; WHO, 2018b). In general, concentrations of geogenic contaminants in groundwater, like arsenic and fluoride, vary only gradually, so may require less frequent monitoring (e.g. once per year); 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 analyzed 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 program.

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 and verification (compliance) monitoring, including the target parameters and the agents involved in each approach.

Operational monitoring is routine monitoring performed by water suppliers to determine if control measures are working properly. Verification (compliance) monitoring is monitoring undertaken to assess if drinking-water meets water quality regulatory standards as defined by government agencies, and it may be performed by water suppliers and/or external authorities (e.g. surveillance agencies). For both operational and verification purposes, risk assessment and mitigation approaches, such as those described in the WHO & IWA's *Water Safety Plan (WSP) Manual*, provide a systematic framework for designing site-specific monitoring programs (Bartram et al., 2009). The WSP approach also makes use of monitoring data to inform the reporting, interpretation and corrective actions to be taken.

Operational monitoring

An operational monitoring plan must consider the parameters to target, their monitoring frequency, 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. In remote or rural settings, 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, in addition to reflecting each parameter's variation rate, an effective and sustainable monitoring program will be tailored to local conditions.

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 residual chlorine 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 delivery to users (WHO, 2017a). 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 paraphenylene diamine) indicator test using a comparator. For the dpd test, a tablet reagent added to a water sample changes the color, and the strength of the color change compared to a standard color chart indicates both total and free residual chlorine concentration ranges. Simple test strips are also easy to use and sufficiently accurate for operational purposes.
- **pH** measures the acidity or alkalinity of water. Where chlorine disinfection is practiced, 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 odor 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, 2017d). 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, 2017a).
- **Structural integrity** may be routinely monitored through system inspections, including assessing the adequacy of source protections, structural integrity of the intake, operational status of treat-

ment devices, and pressure readings throughout the distribution network. Leak detection can inform repairs to reduce the risk of infiltration and backflow. 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.

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Test type	Cost (per-test / equipment)	Incubator required?	Training level	Precision
Presences/ Absence (P/A)	$3.70 / $100	yes	low	N/A
Most Probable Number (MPN)	$10.00 / $0	no	low	low
Colony Count	$2.50 / $200	yes	high	high

Table 2

Comparison of three test kits for detecting *E. coli* in water (adapted from 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, analyzed, 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 program, 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, or 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 data flow diagrams (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 analyze 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 analyzed 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 analyze 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 programs 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.

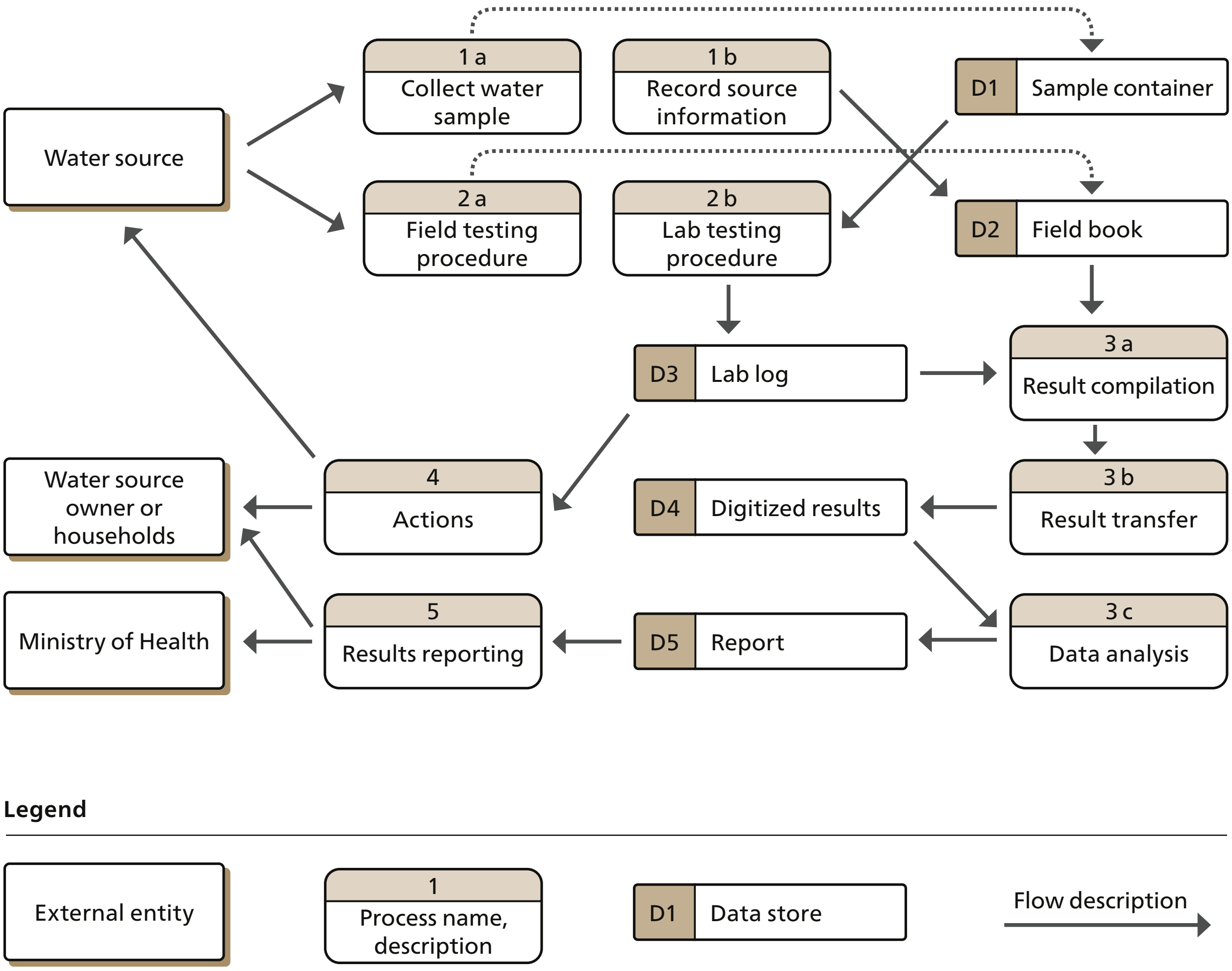

Figure 9

An example data flow diagram (DFD) for a water quality testing program in a monitoring agency in sub-Saharan Africa. The legend shows the four elements of the DFD.

X.11 External support programs

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 programs (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 aging 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 prolong the sustainability 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); however, this service is often some combination of both demand and supply driven. 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 3. 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 The Plurinational State of Bolivia (Davis et al., 2008), El Salvador (Kayser et al., 2014), and the Dominican Republic (Schweitzer and Mihelcic, 2012). Documented benefits reported in these studies consist of improvements in system performance, household satisfaction, water quality, treatment practices, financial stability, and greater 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 program was $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 through the federal government, the Department of Agriculture, and through participatory water system fees.

Circuit Rider programs are also found in Canada, Honduras, El Salvador, Guatemala, 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.

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.

Table 3
Forms of external support programs.

X.12 Climate-resilient water supply

Water supply systems must consider and build 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, 2017c, pS-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, persistence, 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 supplies should assess in detail their current and projected impacts from climate change and consider what managerial, operational, and infrastructural improvements are needed to mitigate these risks.

Climate-resilient water safety planning

Water safety planning (see X.6 Sanitary inspections) 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 (after WHO, 2017c):

- **Augment the water safety plan (WSP) team with relevant climate-related expertise.** An effective team 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);
  - using web-based interactive portals or decision support tools.
- **Identify hazards and assess the risks.** It is important to identify specific hazards/hazardous events associated with the climate information and consider what new hazards may arise from the climate projections. These risks should be assessed and prioritized while considering the impacts of climate on the effectiveness of existing control measures (if present) as well as on the likelihood of the event occurring and the severity of the consequences.
- **Develop an incremental 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/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 4).
- **Develop management procedures and supporting programs 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 alterative 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, loss of supply chains for water treatment chemicals and water quality testing reagents.

Appropriate supporting programs 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 programs 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, 2017c). For smaller community supplies (e.g. Systems 5, 6), refer to *WASH climate resilient development* (UNICEF & GWP, 2014) (Fig. 1). This concept should be applied equally to new water supply systems at the planning stage as well as to existing systems to strengthen resilience to future anticipated and unanticipated events arising from climate change.

Resilience to other emergencies

Enhancing resiliency to climate impacts can also support preparedness for other unforeseen impacts on water supply systems, such as natural disasters (e.g. earthquakes) and 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.

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 program to minimize water wastage **Distribution/storage** Leak detection/mains repair program **Household** User outreach and education program on water conservation during drought Diversification of household water supply to include safe rainwater harvesting practices

Table 4
Examples of improvement measures to manage priority risks from climate change at various stages of a water supply system.

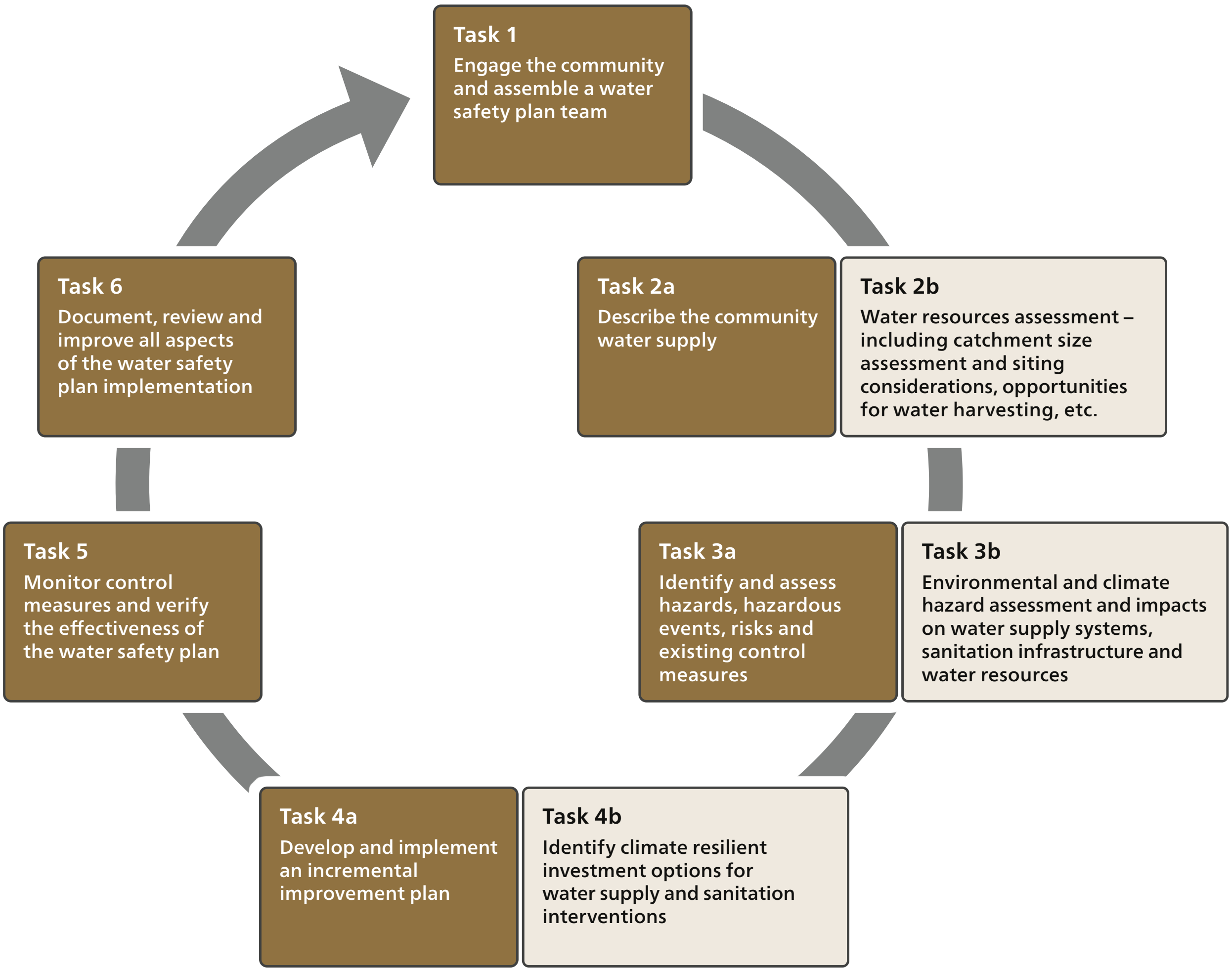

Figure 10

Water safety planning adapted for climate resilience in small community settings (UNICEF and GWP, 2014).

Acronyms

AC	alternating current
AC	activated carbon
BSF	biosand filter
CDC	Centre for Disease Control
CIP	cleaning in place
COD	chemical oxygen demand
DC	direct current
DFD	data flow diagrams
DNA	deoxyribonucleic acids
E. coli	Escherichia coli
EBCT	empty bed contact time
ESP	external support program
FAO	Food and Agriculture Organization
GAC	granular activated carbon
GIS	geographic information system
GPS	global positioning system
HDPE	high density polyethylene
HTH	high test hypochlorite
ICT	Information and Communications Technology
IRC	International Reference Centre
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
LEDs	light-emitting diodes
LRV	log reduction value
MD	membrane distillation
MF	microfiltration
MPN	most probable number
NF	nanofiltration
NGO	non-governmental organization
NPSH	net positive suction head
NTU	nephelometric turbidity units
P/A	presence/absence
PET	polyethylene terephthalate
PP	polypropylene
PV	photovoltaic
PVC	polyvinyl chloride
QMRA	quantitative microbial risk assessment
RNA	ribonucleic acids
RO	reverse osmosis
SDG	Sustainable Development Goal
SI	sanitary inspection
SODIS	solar disinfection
SPPS	solar-powered pumping systems
SSF	slow sand filter
TDS	total dissolved solids
UF	ultrafiltration
UN	United Nations
UNDP	United Nations Development Programme
uPVC	unplasticized polyvinyl chloride
UV	ultraviolet
UVT	ultraviolet transmittance
VFD	variable-frequency drive
WHO	World Health Organization
WSP	water safety plan

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 neutralise 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 (1,000–10,000 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 electro-chlorination 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 capaci-ty 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 destabilise 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 if the water quality complies with the regulatory or voluntary drinking-water quality standards.

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 affect public health if present in levels above water safety standards.

Control measure: Activities or processes to prevent or eliminate a water safety hazard/hazardous event, or reduce it 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 way, 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 harvest-ing systems that is diverted away from the storage tank.

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

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

Flux: Flow rate per area of membrane.

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

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, handwashing 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 which may adversely affect the supply of safe drinking-water. May include microbial, chemical, physical, or radiological agents that can cause harm to public health, or a condition that affects the quantity of water available.

Hazardous event: An event by which a hazard is introduced to, or is inadequately removed from, the water supply system.

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 or the usefulness for groundwater supply 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 develop-ment 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 corre-sponds 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 shone through a water sample 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.

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 something that had been disinfected becoming contaminated again (e.g. water that was treated at water system level becomes recontaminated 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 chlorine: The amount of active (free) chlorine remaining in the water after a certain period of time (i.e. 30 minutes of contact time) when the initial chlorine demand has been met (syn.: free chlorine residual).

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 that a hazardous event will occur and the severity of its 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 particles 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 programs: 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: Confirms if the Water Safety Plan as a whole is working effectively to deliver safe 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.

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Part 1: System Templates

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

System 1 Rainwater harvesting

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System 2 Centralized surface water treatment

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

System 3 Decentralized surface water treatment

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

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

This sheet has been adapted from: Breitenmoser L. Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

System 6 Gravity flow supplies

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

System 7 Groundwater subjected to geogenic contamination

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

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System 8 Freshwater sources subjected to anthropogenic contamination

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System 9 Desalination of brackish and sea water

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Part 2: Technology Information Sheets

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S.3 Spring water

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S.4 Rivers and streams

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S.5 Ponds, lakes, and reservoirs

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S.6 Brackish water, seawater

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I. Intake

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I.1 Roof water collection system

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I.2 Rainwater catchment dam

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A. Abstraction

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T. Treatment

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

T.1 Clarification

T.1.1 Roughing filtration

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T.1.3 Microfiltration

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

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T.1.4 Coagulation/flocculation/sedimentation

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

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T.1.5 Coagulation/flocculation/filtration

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T.2 Removal/inactivation of microorganisms

T.2.1 Chlorination

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

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T.2.3 Ultraviolet (UV) light disinfection

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

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T.2.4 Slow sand filtration

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

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T.2.5 Ultrafiltration

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

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T.2.6 Pasteurization

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T.3 Treatments for geogenic contaminants

T.3.1 Fluoride removal methods

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T.3.2 Arsenic removal methods

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

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T.4 Treatments for organic and inorganic contaminants

T.4.1 Activated carbon

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T.4.3 Nanofiltration

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T.5 Desalination

T.5.1 Membrane distillation

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T.5.2 Reverse osmosis

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D. Distribution and transport

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

D.1 Jerry cans

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

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D.2 Water vendors (carts and trucks)

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

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D.3 Water kiosk

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D.4 Small public and community distribution systems

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D.5 Centralized distribution systems

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D.6 Storage tanks or reservoirs

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H. Household water treatment and safe storage

This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

H.1 Storage tanks or reservoirs This sheet has been adapted from: Breitenmoser L., Peter M., Kazner C. 2016. Compendium of Water Systems and Technologies from Source to Consumer. D8.7 Water4India Horizon Report, FHNW, Muttenz, Switzerland

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H.2 Ceramic filtration

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H.3 Ultrafiltration

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H.4 Chemical disinfection

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H.5 Boiling

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Part 3: Cross-cutting issues

Cross-cutting issues (Introduction)

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