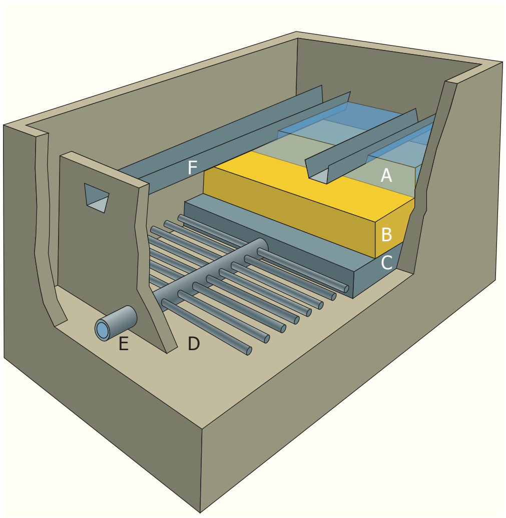
Surface water



Contents

This handout is based on *Drinking Water, Principles and Practices* by de Moel et al.

1. Introduction

Populated areas are often located in river deltas, where surface water is abundantly available and where it can be abstracted rather easily in large amounts.

However, compared to groundwater, surface water shows very large variations in available quantity as well as in quality. The variations in quantity and quality can be such that the water is temporarily not available or not suitable for the production of drinking water. For these periods, large storage facilities are required, also because contamination of river water by ships or industrial wastewater cannot be prevented.

In the production of drinking water from surface water, two different approaches can be distinguished:
- direct treatment of surface water
- indirect treatment of surface water via infiltration

Surface water can be found in several natural forms: rivers and lakes and man-made forms such as canals, reservoirs and gravel and sand extraction pits

Rivers and canals

High up in the mountains river water is only minimally contaminated and contains few dissolved minerals. Therefore, it is highly attractive as a source for water supply.
In the middle course of the river, the flow is greater and less variable, and the amount of dissolved solids is also greater. In the lower course of the river, the water is highly mineralized and contaminated with residential and industrial wastewater. Accidental contaminations are always to be feared.

In the Netherlands, the Rhine is one of the rivers that is used for drinking water supply. The Rhine is a glacier/rain river with peak flows in winter and spring (ca. 2,500 m^3/s) and a relatively high minimum flow (ca. 1,500 m^3/s). The catchment area includes large parts of Switzerland, Germany, France, Luxembourg and the Netherlands (Figure 1). High population density, strong industrialization and extensive navigation leave definite marks on the water quality (e.g., a high salt content). Rhine water is mainly abstracted indirectly from canals and lakes fed by the river, or by riverbank filtration along the Lek and IJssel rivers (which are fed by the Rhine).

Canals have characteristics similar to a river. They are not only used for navigation but also as a means to transport surface water. This is done for irrigation purposes, drainage of surplus rainwater, and for the prevention or limitation of salt intrusion.

Figure 1 - Catchment area of the Rhine

Lakes and reservoirs

Because of their large surface area, lakes have a less variable supply capacity than rivers, and their large volume leads to a stable water quality . When incidental discharges of pollutants are expected, separated reservoirs should be built. However, because of self-purification, the water quality typically improves on its own. Sedimentation clarifies the water, ammonium and organic matter are oxidised, and the hygienic quality improves because fecal bacteria die of natural causes.

For water abstraction, stratification in deep eutrophic lakes is rather disadvantageous. The water below the metalimnion (Figure 2) is useless because of its anaerobic condition, while the water above the metalimnion is unattractive because of its high algae content. A significant quality improvement can be achieved by mixing, as this will bring the deep water temporarily to the surface, while the algae growth is slowed down by the lack of light in deep waters.
In the Netherlands, the IJsselmeer lake is used to supply drinking water. The IJsselmeer is a large, shallow lake (depth 3 - 5 m, 1,100 km^2) that is flushed with Rhine water (via the IJssel River) and drainage water from surrounding polders. Residence time in the lake is about four months. The abstraction at Andijk is used for the direct production of drinking water (ca. 25 million m^3/y, ca. 1 m^3/s), and for the production of drinking water by means of infiltration into the dunes as well as for industrial water (total 110 million m^3/y, ca. 4 m^3/s).

Reservoirs are artificial lakes, created by the construction of a dam (Figure 3) or by the construction

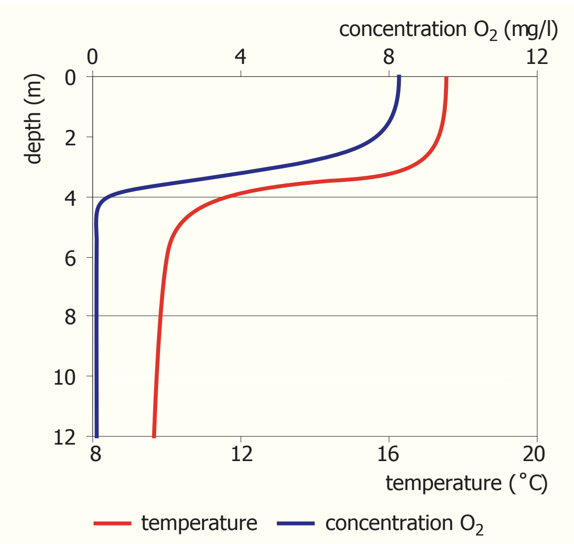


Figure 2 - Thermocline in eutrophic lakes

of a surrounding dike. Reservoirs dampen the variation in a river's flow, making a steady abstraction of water possible for irrigation, water supply or energy production via a power plant.

Figure 3 - Hoover Dam in the Colorado River (USA)

2. Direct treatment of surface water

2.1 Historic development

From a global point of view, the direct treatment of surface water is the most applied method for drinking water production. This is mainly because large cities have developed along river banks, making surface water directly available.

Throughout the ages, because of both the increasing quantitative demand (population growth, consumption growth) and the increasing qualitative demand (worse sources, more stringent quality legislation), direct treatment methods for drinking water production have changed drastically.

Traditionally, direct treatment was performed by clarification in large sedimentation basins and subsequent slow sand filtration. Characteristic of this procedure was the enormous spatial demand and the labor intensive operation (manual removing of the "Schmutzdecke" from the slow sand filter).

By adding rapid filtration, the load on the slow sand filtration was decreased, increasing the production capacity with the use of the traditional means. To guarantee the microbiological (e.g. bacteriological) quality of the drinking water, a safety chlorination was applied as a final step in the treatment process. This leads to the presence of a small concentration of chlorine in the water at the customers' taps.

Meanwhile, the production needed to be increased. Thus, the rapid filtration system became heavily loaded, resulting in too short run times between backwashing. The problem was solved by adding a coagulant before sedimentation to increase the effectiveness of the process.

When production demands increased further, the surface area of the slow sand filtration installation became the bottleneck. The slow sand filtration not only removed suspended solids, but removed (pathogenic) microorganisms as well. Slow sand filtration was therefore, increasingly replaced by chemical disinfection .

Increased river contamination led to the construction of reservoirs to prevent direct intake of river water.
The reservoirs were shallow basins at first, where a considerable algal population could develop during spring and summer. Algae can cause taste and odor problems. Besides, their removal by sedimentation is very difficult unless very high doses of flocculants are used. Thus, microstrainers were introduced as the first treatment step. Since the 1970s mainly deep reservoirs have been used. In these deep reservoirs, algae growth can be quite well controlled, making the microstrainers obsolete. Using deep reservoirs with a very long residence time yields a considerable amount of self-purification in the basins as well.
Water from such reservoirs is typified by a low concentration of suspended solids (<5 mg/l), few algae, and a low ammonium concentration. With this water quality, sedimentation is sometimes unnecessary, and a very low dose of coagulant followed by rapid sand filtration can be used.

Finally, when micropollutants limits were included in water quality standards, activated carbon (i.e., dosing of powdered activated carbon, PAC) was added to the traditional treatment. Such traditional treatment process (Figure 4) is still widely applied around the world.

2.2 Contemporary treatment

Problems with the traditional treatment process

Contemporary treatment originated from the increased river water pollution and the chlorination issue. In 1974 J. Rook, of the Rotterdam Water Company, discovered harmful by-products from the chlorination process (disinfectant by-products). These are mainly trihalomethanes (THMs), from which chloroform ($CHCl_3$) is produced at the highest level. THMs are created by the reaction of chlorine with humic acids present in the water, and are harmful to human health. The Dutch Decree on Water Supply sets a standard of 25 μg/l (sum) for THMs. Chlorination may lead to exceedance

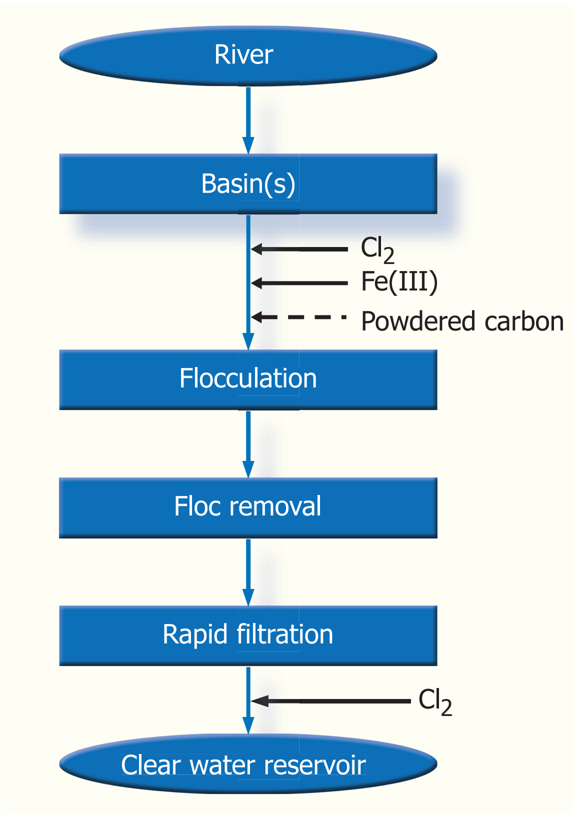


Figure 4- Traditional treatment scheme for direct treatment of surface water

of this standard; but without sufficient chlorination, the disinfection would not be enough to meet the hygienic standards. For this reason, the Dutch Decree allowed temporarily a THM value of 100 μg/l (until January 1, 2006).

In 1987 the herbicide Bentazon was found in Amsterdam's drinking water. Like many micropollutants, such as Atrazin and Diuron, this herbicide proved to be insufficiently removed in the treatment process, even in the case of artificial infiltration into sand dunes. Therefore, activated carbon filtration, which efficiently removes these pollutants, became part of any contemporary treatment.

In 1993, a severe Cryptosporidium outbreak occurred in Milwaukee, Wisconsin (USA), resulting in 400,000 ill people and 100 deaths. Chlorination did not prove to be a sufficient barrier to cysts like Cryptosporidium and Giardia and the use of higher doses and longer contact times could produce trihalomethanes (THMs). Alternatives to this are stronger disinfectants like chlorine dioxide (ClO_2) or ozone (O_3).
Chlorine dioxide also produces by-products, but less than when using chlorine or hypochlorite. Disinfection using ozone can produce bromate, which is also harmful to public health. However, because sufficient disinfection is essential for the drinking water supply, the Dutch Decree on Water Supply allows an increase in the maximum bromate concentration from 1.0 μg/l to 5.0 μg/l when using ozone disinfection.

Contemporary treatment steps
The steps used for contemporary direct treatment of surface water thus include:

- storage reservoirs with a retention time of 1 - 3 months, making an intake stop possible in case of severe river contamination, and with a depth of over 20 meters to control algae growth
- process reservoirs with a retention time of about 1 month and a depth of over 20 meters, leading to a significant self-purification (sedimentation of suspended solids, ammonium oxidation) while still keeping algae growth under control
- Coagulation-flocculation and floc removal by filtration, possibly preceded by sedimentation or flotation, for removal of suspended solids
- primary disinfection using a minimum amount of chlorine or ozone
- activated carbon filtration for the removal of micropollutants
- secondary disinfection using a minimum amount of chlorine or chlorine dioxide

Example of contemporary direct treatment (chlorine and activated carbon filtration)

An example of contemporary direct treatment can be found at the Berenplaat production plant (Figures 5 and 6).
At this site drinking water is produced from Meuse water, which has first been stored in the Biesbosch storage reservoirs.

To disinfect the water, hypochlorite is added (about 1 mg/l as Cl_2) for half an hour, which is done in a tank with a canal labyrinth. After this phase a flocculant is added (ca. 5 mg/l Fe^{3+} in the form of $FeCl_3$) for the coagulation of suspended solids, and then lime is added to correct the pH value of the water (ca. 6 mg/l in the form of CaO). When necessary, a flocculant aid (ca. 1 mg/l in the form of Wispro in winter) and powdered activated carbon (ca. 7.5 mg/l in case of severe pollution) are added. The added chemicals are mixed with the water using mechanical stirrers for rapid mixing.

The addition of $FeCl_3$ is used for the removal of suspended solids that remain in the water after the storage reservoirs. The Fe^{3+} together with the lime OH^- form small $Fe(OH)_3$ flocs around the particles. Mechanical stirrers cause turbulence in the water and the flocs collide and grow (flocculation). A flocculant aid can accelerate this process.

Flocs are removed by a floc-blanket clarifier. The total retention time in the floc-blanket clarifier is about one hour at a sedimentation rate of not more than 4.8 m/h. The settled flocs (sludge) are drained into a very large sedimentation basin, where they accumulate at the bottom.

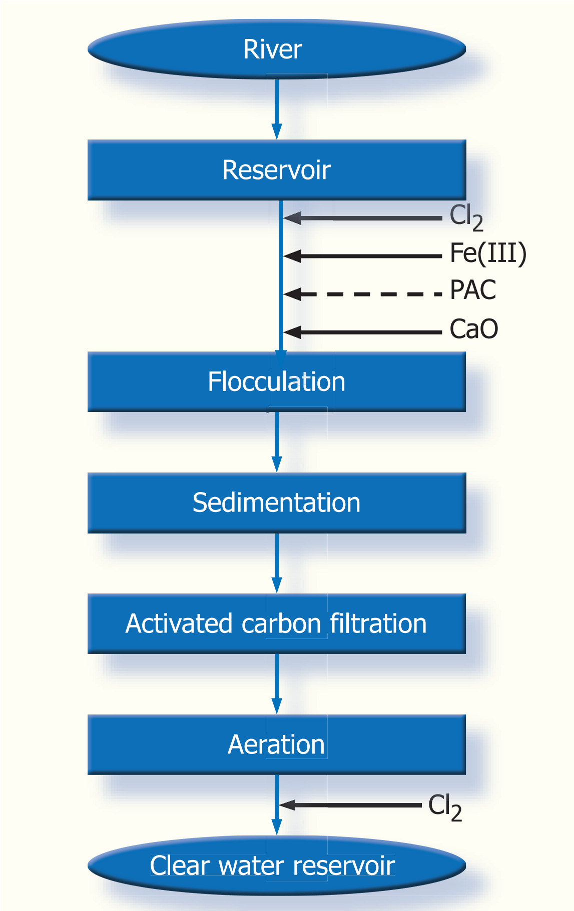


Figure 5 - Contemporary direct treatment of surface water (Berenplaat)

To remove the remaining turbidity, taste, odor, and micropollutants, the water is treated using activated carbon filters. The filters consist of a layer of granular activated carbon at a height of 1.1 meters, applied over a supportive gravel layer. The filtration rate is no more than 9.4 m/h, equivalent to an approximate retention time (empty bed contact time) of 7 minutes minimum.

Since the filters will slowly clog, they need to be backwashed with clean water in an upward direction every few days. Carbon activity decreases over time, so the carbon must be reactivated every 1 - 1.5 years.

After pumping the water into clear water reservoirs there is a step of cascade aeration. This way, there is an increase of oxygen which could be previously low due to biological processes. Chlorine dosing is used in order to have a minimum biological activity during the treatment process.

To prevent regrowth during transportation, hypochlorite is added before the clear water reservoirs (ca. 0.5 mg/l as Cl_2).

The data shown in Table 1 indicate the water quality of the untreated and treated water. The raw water has a high pH value, caused by sodium hydroxide softening in the Biesbosch reservoirs.

Due to the formation of $Fe(OH)_3$ the pH value is reduced, and by adding lime it is raised again to the desired level. The suspended solids are mainly removed in the floc-blanket clarifiers and during (activated carbon) filtration. Chlorination results in an increased chloroform concentration and a reduced E.coli number.

Example of contemporary direct treatment (ozone with activated carbon filtration)
An example of contemporary direct treatment can be found at the Kralingen production plant (Figures 7 and 8). At this site drinking water is produced

Table 1 - Quality data of the raw and clear water at the Berenplaat drinking water production plant (Zuid-Holland)

Parameter	Unit	Raw water	Clear water
Temperature	°C	11.9	11.9
pH	-	9	8.1
EC	mS/m	51	54
SI	-	0.9	0.1
Turbidity	FTU	2	0.1
Na^+	mg/l	46	49
K^+	mg/l	6	6
Ca^{2+}	mg/l	51	54
Mg^{2+}	mg/l	8	8
Cl^-	mg/l	72	74
HCO_3^-	mg/l	87	95
SO_4^{2-}	mg/l	64	83
NO_3^-	mg/l	3	3
O_2	mg/l	11.1	10.8
CH_4	mg/l	-	-
CO_2	mg/l	0.3	1.3
Fe^{2+}	mg/l	-	-
Mn^{2+}	mg/l	-	-
NH_4^+	mg/l	-	-
DOC	mg/l	3.6	2.6
E-Coli	n/100 ml	100	0
Bentazon	µg/l	0.2	< 0.1
Chloroform	µg/l	0	38
Bromate	µg/l	< 2	2.0

Figure 6 - Drinking water production at the Berenplaat production plant (Zuid-Holland)

from Meuse water, which has first been stored in the Biesbosch storage reservoirs.
At the Kralingen plant a coagulant is added first (ca. 4 mg/l Fe^{3+} in the form of $FeCl_3$), before the water goes through a static mixer. This leads to the formation of small $Fe(OH)_3$ flocs and to the removal of pollutants from the water. If necessary, a flocculant aid (ca. 1 mg/l in the form of Wispro, during winter) is added. In four serial flocculation compartments having a total retention time of at least 20 minutes, slowly rotating mixers are used to grow flocs. The mixing decreases in intensity in each consecutive compartment in order to prevent flocs from being broken up. The flocs are removed in a lamella separator where they settle between tilted plates. This arrangement creates an enormous settling surface in a relatively small area. Particles with a sedimentation rate of over 1.2 m/h are all separated in this installation. The settled flocs slide down over the plates into a sludge thickener, which is equipped with stirrers. The thickened sludge is pumped to sludge-drying beds for dewatering.

After the floc formation and removal, sulfuric acid is added to lower the pH, because ozone is more effective at low pH values. By means of a diffuser, ozone is injected into the water (ca. 1.2 - 2.0 mg/l in the form of O_3). The ozone spreads through the water in the form of fine dissolving bubbles, being active there during a contact period of 8 - 10 minutes. Ozone is used to kill pathogenic micro-organisms (bacteria, viruses and protozoa), to degrade micropollutants, and to improve the taste of the water.

To remove the remaining turbidity, the water is treated in a dual-layer sand filter. For an effective performance of this filter an extra coagulant is added (ca. 0.5 mg/l Fe^{3+} in the form of $FeCl_3$).

The sand filters have a surface area of 9 by 4 m and consist of a sand layer of 0.7 m and an anthra-

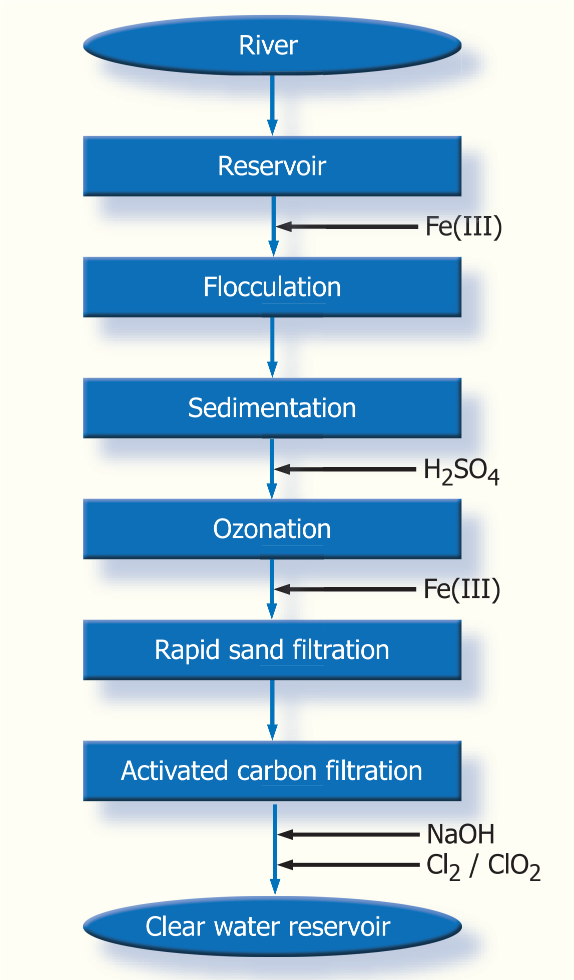


Figure 7 - Contemporary direct treatment of surface water with ozonization (Kralingen)

cite layer of 0.8 m. Below these layers there is a gravel support layer. The filtration rate is 20 m/h maximum. Because the filters clog, they are back-washed daily with air (max. 80 Nm/h) and water (max. 45 m/h) in an upward direction.

Subsequently, the filtered water is treated with activated carbon for an approximate contact period (empty bed contact time) of 10 minutes. There the remaining micropollutants and the taste and odor are removed. Because the activated carbon activity decreases in time, it needs to be reactivated every 1 - 2 years. Besides, every two to three weeks the filters need to be backwashed in order to remove suspended solids. After the activated carbon treatment, sodium hydroxide is added to correct the pH value.

To make sure that microbiological regrowth does not occur during istribution, hypochlorite is added (ca. 0.3 mg/l in the form of Cl_2).

Table 2 shows the water quality of both the raw and treated water. The raw water has a high pH value, caused by the softening with sodium hydroxide in the Biesbosch reservoirs. Due to formation of $Fe(OH)_3$ and sulfuric acid, the pH value is reduced, and by adding sodium hydroxide it is increased again to the normal value. The suspended solids are mainly removed in the lamella separators and the dual-layer filters. Adding ozone results in an increased bromate content and a reduced E.coli number.

The concentrations of DOC and Bentazon are reduced during the activated carbon filtration. The low chlorine dosing results in a small increase in chloroform in the water.

2.3 *Modern treatment*

Problems of contemporary treatment

Table 2 - Quality data of the raw and clear water of the Kralingen production plant (Zuid-Holland)

Parameter	Unit	Raw water	Clear water
Temperature	°C	11.9	12.1
pH	-	9	8.2
EC	mS/m	51	55
SI	-	0.9	0.1
Turbidity	FTU	2	0.05
Na^+	mg/l	46	52
K^+	mg/l	6	6
Ca^{2+}	mg/l	51	51
Mg^{2+}	mg/l	8	8
Cl^-	mg/l	72	73
HCO_3^-	mg/l	87	94
SO_4^{2-}	mg/l	64	85
NO_3^-	mg/l	3	3
O_2	mg/l	11.1	10.2
CH_4	mg/l	-	-
CO_2	mg/l	0.3	0.9
Fe^{2+}	mg/l	-	-
Mn^{2+}	mg/l	-	-
NH_4^+	mg/l	-	-
DOC	mg/l	3.6	1.9
E-Coli	n/100 ml	100	0
Bentazon	µg/l	0.2	< 0.1
Chloroform	µg/l	0	1.8
Bromate	µg/l	< 2.0	3.9

Figure 8 - Kralingen drinking water production plant (Zuid-Holland)

Contemporary treatment techniques still face some problems, such as the by-products (THMs and bromates) that are formed during disinfection and oxidation, due to the discovery of new emerging micropollutants, and the required prevention of Legionella.
Effective removal of Cryptosporidium and Giardia requires a high dose ozone. The tightened regulations regarding bromate make this more difficult. Besides, new and difficult to remove polar micropollutants have been discovered. These compounds may also require an oxidation process with high doses, which will again give rise to the formation of undesirable by-products.

Figure 9 - Future treatment of surface water: physical or chemical

In addition, the increase of hormones in surface water (i.e., estrogen) and materials which act as endocrine disruptors and lead to hormonal deviations will be important in future drinking water production from surface water. Finally, the Legionella issue will require an improved water quality in order to reduce Legionella growth in the distribution network. This will require a further reduction in the amount of assimilable organic matter (AOC) in the water to prevent regrowth of bacteria.

The above developments will necessitate a renewed orientation of the integral setup of treatment schemes for the direct production of drinking water from surface water. It may be that biological and physical processes will increasingly take over the role of the chemical processes for disinfection and oxidation (Figure 9).

Figure 10 - Biologically activated carbon filtration at Berenplaat production plant (Zuid-Holland)

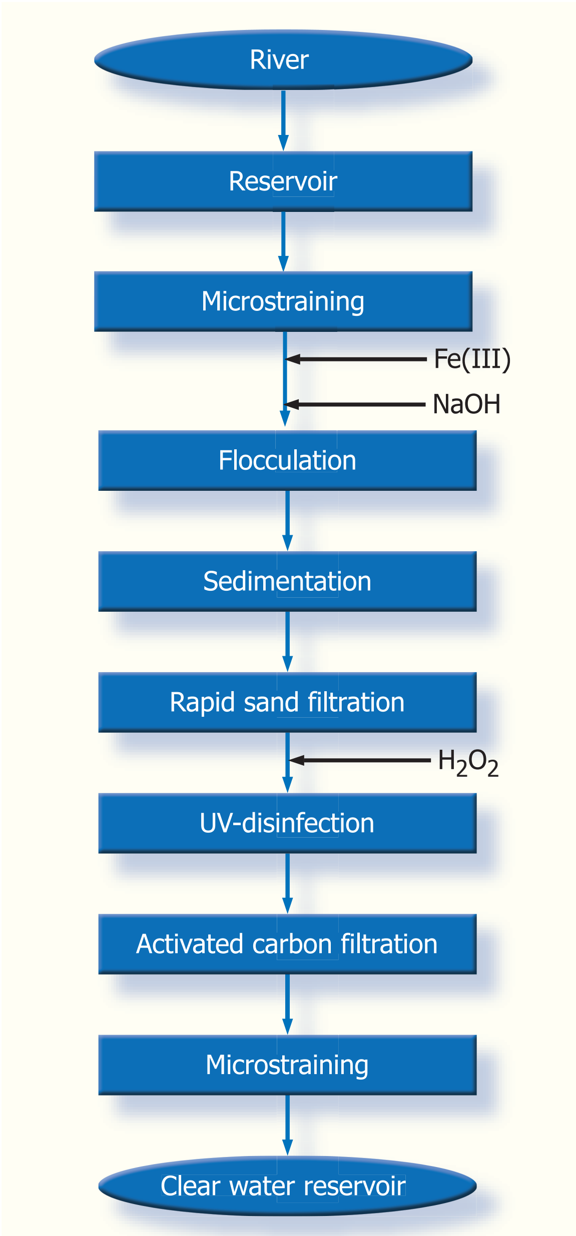


Figure 11 - Direct treatment of surface water at Andijk production plant (2005)

Figure 12 - UV / H_2O_2 (Andijk)

Biological processes

In biological processes, pollutants are assimilated by biomass and therefore removed from the water. Besides, biological processes result in reduced amounts of organic matter (DOC, AOC, etc.). The treated water should be biologically stable, so that the biological activity in the distribution network is low and residual disinfection is unnecessary.

The biological processes that are currently considered for large-scale application are:

- biologically activated carbon filtration (Figure 10)
- slow sand filtration

Physical processes

Physical processes currently being considered for large-scale applications are:

- UV disinfection
- membrane filtration

By exposing the water to UV radiation, the DNA structure of organisms is destroyed, thereby stopping growth. It has proved to be very effective to combine UV disinfection with hydrogen peroxide as a strong oxidant. Both processes have not shown any harmful side-effects to date. An example of such a system is the Noord-Holland (Andijk) water supply (Figures 11 and 12).

With membrane filtration, the water is pressurized through a membrane. These membranes are available in several different pore sizes (Figure 13).

Ultra- and microfiltration mainly retain the coarser pollutants like suspended solids, cysts and bac-

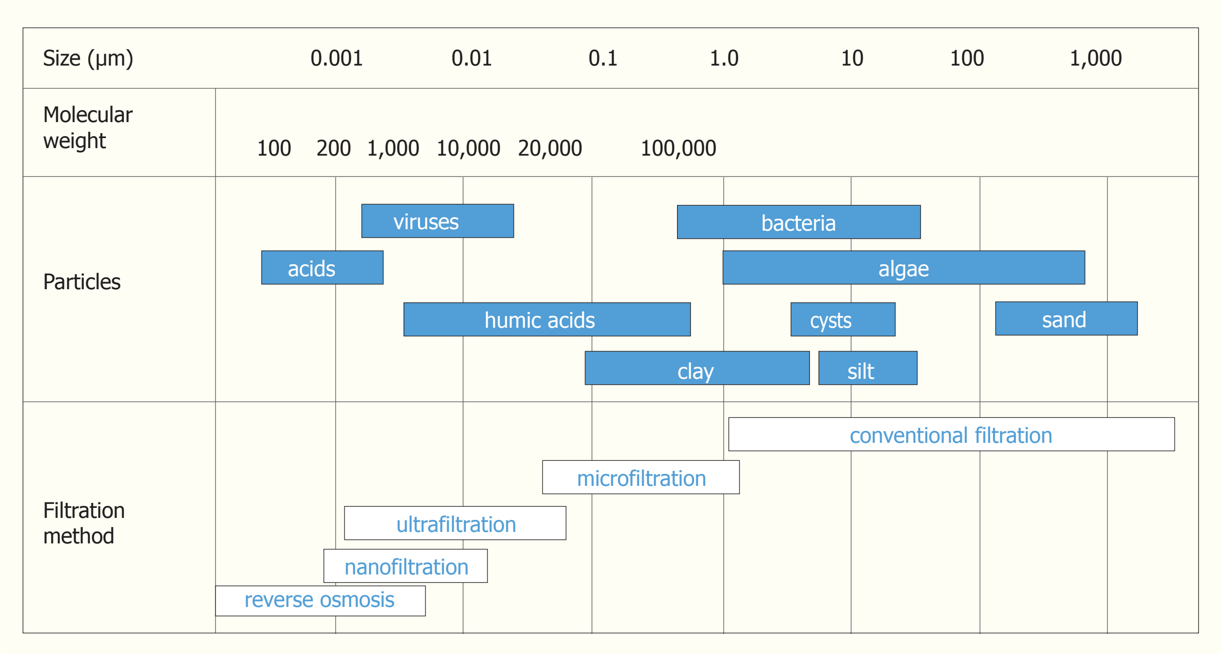


Figure 13 - Application fields for membrane filtration

teria. Nanofiltration also retains divalent ions, like Ca^{2+}, SO_4^{2-} etc., most larger organic compounds (humic acids), and most micropollutants. Here, cysts, bacteria and viruses are entirely filtered out. Reverse osmosis increases the filtration to monovalent ions and almost any micropollutant.

There are some objections to the application of membrane filtration:

- risk of membrane defects and thus incomplete disinfection
- disposal of concentrate
- high costs of construction and operation

Recently, a treatment plant based on membrane filtration (ultrafiltration followed by reverse osmosis, Figures 14 and 15) was started up in Noord-Holland (Wijk aan Zee). The produced water is mixed with drinking water from a system of artificially infiltrated surface water.

Figure 14 - Membrane filtration plant in Heemskerk (Noord-Holland)

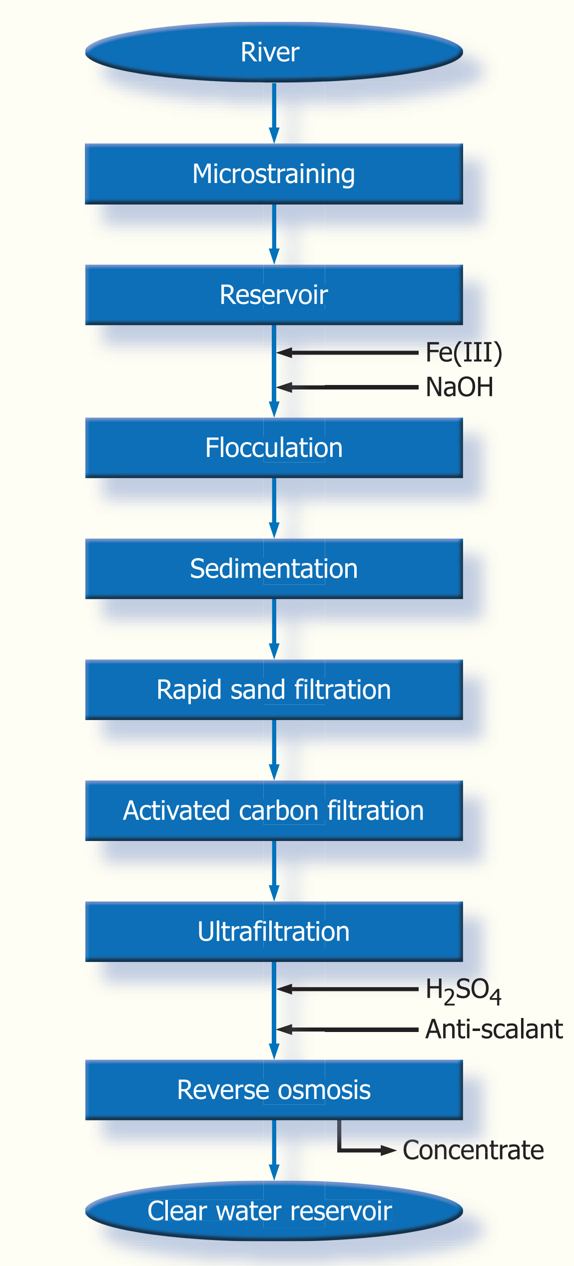


Figure 15 - Direct treatment of surface water at Heemskerk production plant