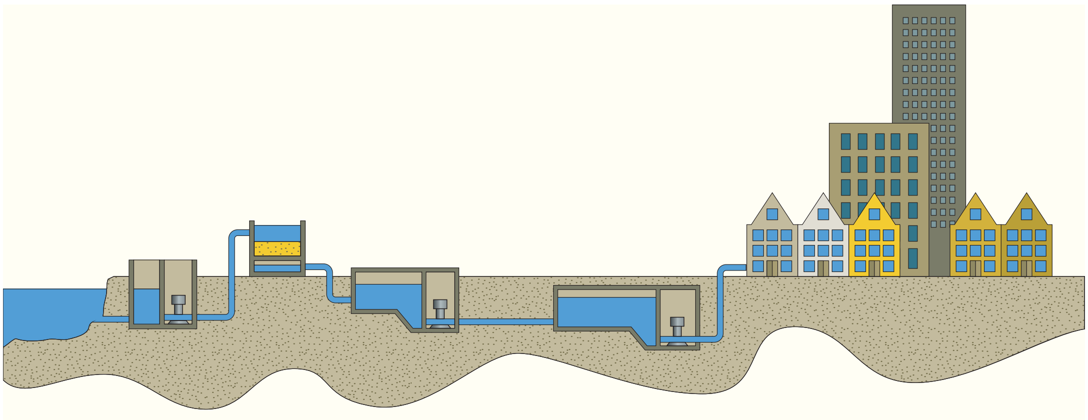
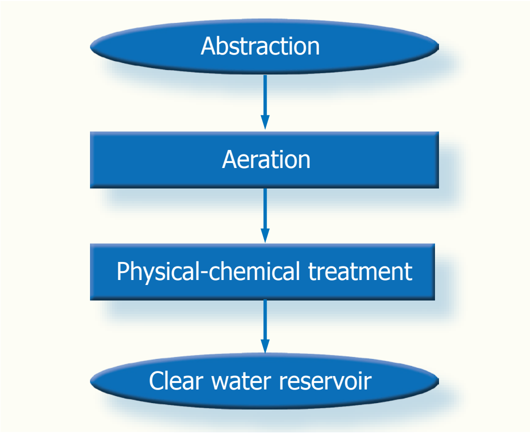
WATER TREATMENT

Water treatment schemes





Framework

This module represents a short introduction to treatment schemes used for the production of drinking water.

Contents

This module has the following contents:

Study goals

After having studied this module, you will be able to:

- understand treatment schemes for groundwater and surface water

1. Introduction

For personal hygiene and other domestic activities (washing, cleaning, toilet flushing, etc.), it is important to have sufficient water available. In addition, for consumption, water of good quality is essential.

More than 99% of Dutch households receive their water via a public water supply.
This water is hygienically reliable, clear, good tasting and of a pleasant temperature. The water is distributed through piped networks under sufficient pressure for even the most remote houses. High quality drinking water is supplied into people's homes at a very "low" price.
The Dutch water supply system is one of the best-known systems in the world.

In public water supply, five components may be distinguished (Figure 1):

- abstraction
- treatment
- transport
- storage
- distribution.

Raw water can be abstracted from groundwater or surface water. For almost every type of water, a corresponding treatment is necessary before it can be supplied as drinking water. During transport, storage and distribution, the quality of the drinking water must not deteriorate below the established standards.

The purpose of placing a low-lying, clear water reservoir after the treatment step is to adjust the differences between the treatment plant and the

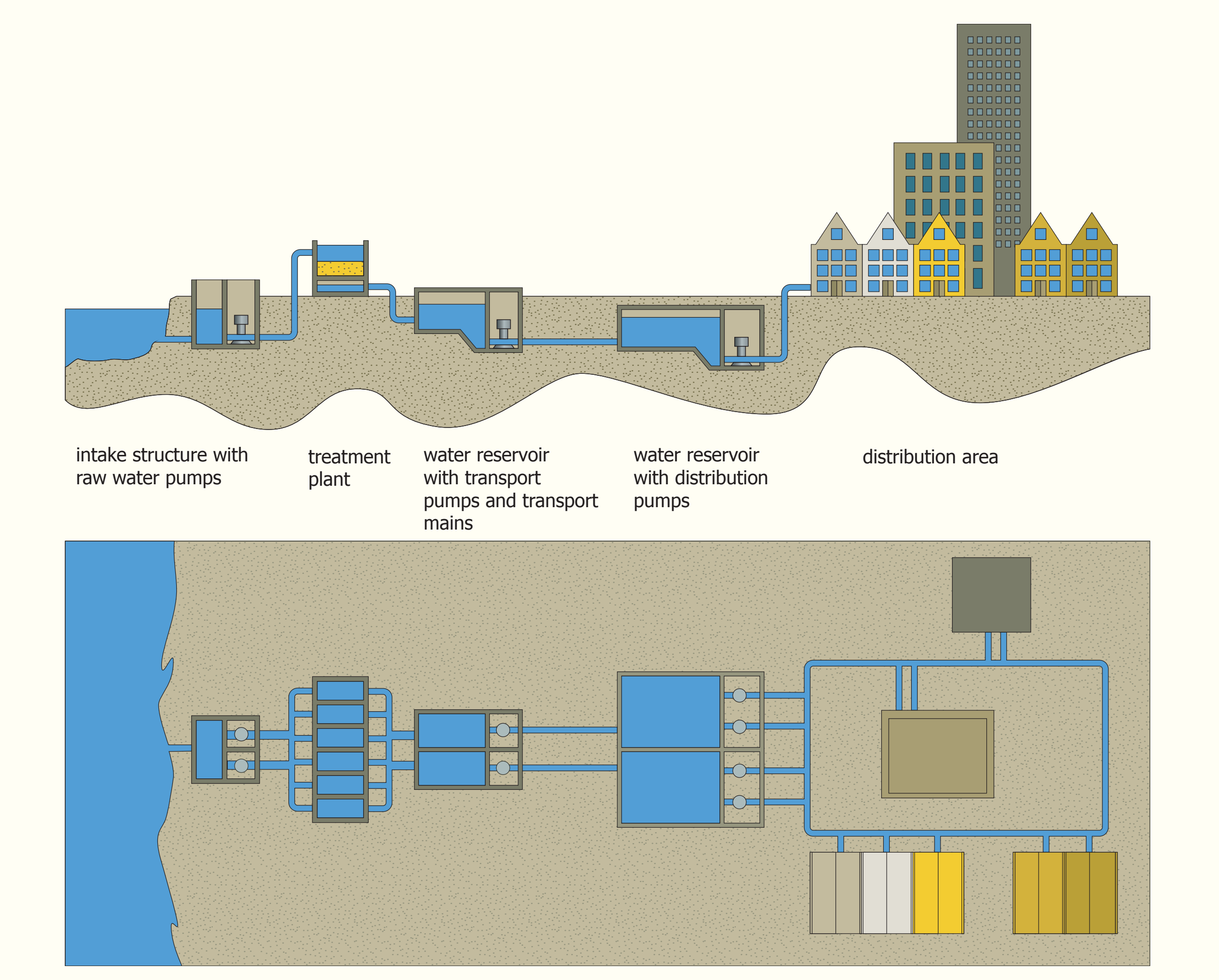


Figure 1 - Drinking water supply of a city

transport pumps.

A distribution reservoir at the edge of the city levels off consumption variations between day and night, resulting in a constant flow through the treatment plant and the transport main, and in minimal energy consumption.

The drinking water is distributed continuously under sufficient pressure (>20 meters water column (200 kPa) above street level). This pressure also prevents infiltration of the groundwater into the distribution system, which would result in quality deterioration.

Because drinking water quality is only required for human consumption (5 % of the total production), separate water supplies with different qualities could be considered. The distribution network, however, is the most expensive element of the public water supply. The costs are up to 50 to 70% of the total water price. The savings on treatment costs do not compensate for the extra costs for supply and distribution and the risks to public health (by cross-connections).

Domestic water consumption in the Netherlands is still increasing, despite efforts to encourage consumers to save water (Figure 2).

In addition, the standards for drinking water have become more rigorous and knowledge about contamination and its effects on public health is increasing.

Important developments are the discovery of harmful byproducts that are formed during the chemical disinfection of drinking water.

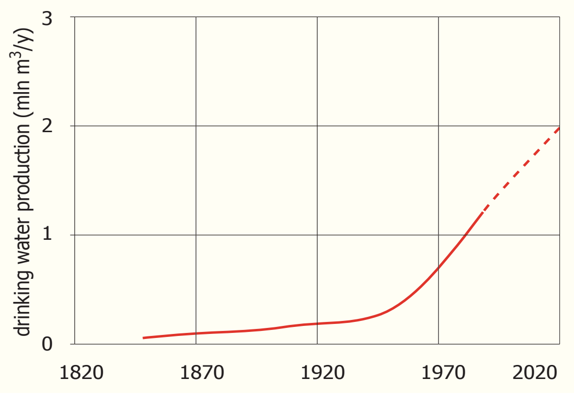


Figure 2 - Drinking water production in the Netherlands

Parallel to these developments, the discovery of pesticides in raw water and drinking water (the Bentazon-affair at Amsterdam Water Supply in 1987) has led to changes in opinions about drinking water production.

Additionally, many water companies have set guidelines for the maximum hardness of drinking water. Hard water can cause lime deposits in warm water installations and reduce the formation of foam from soap. Hence, energy and soap consumption increase.

Also, more rigorous environmental standards have led to better treatment of surface water before it is infiltrated.

Finally, backwash water for the filters is more often treated and recirculated.

The above implies that, in the near future, the infrastructure must be expanded and improved.

For civil engineers this creates a great challenge.

The design of the components of a drinking water supply system requires not only knowledge of sanitary engineering, but also knowledge of other disciplines as well.

Knowledge of water management is necessary when determining the source location and for minimizing the consequences of the abstraction on the environment and other activities (e.g., agriculture, navigation).

In addition, there is a need for fluid mechanics and structural engineering to determine the dimensions of pipes, pumps, treatment installations and reservoirs.

Finally, knowledge of chemical engineering and biotechnology is needed to design and optimize treatment processes.

2. Groundwater

2.1 Types of groundwater

Groundwater has a near-constant quality. Per location, however, large differences in water composition can be found.

This composition is a result of the natural environment from which the groundwater is abstracted, and the route that the water has followed to get there.

Three types of groundwater can be roughly distinguished with respect to the treatment in drinking water production:
- aerobic groundwater (phreatic)
- slightly anaerobic groundwater
- deep anaerobic groundwater

The above list implies that, for the treatment of groundwater, the level of oxygen (aerobic, slightly or deep anaerobic) is very important.
The redox potential is a good indicator for this, but this potential is seldom measured in practice. To what type a certain groundwater belongs can be determined from the concentrations of oxygen, iron, and methane.
The three types of groundwater will be further discussed separately, on both their typical characteristics and their treatment schemes. After this the different treatment processes will be described.

2.2 *Aerobic groundwater (phreatic)*

Phreatic groundwater has an open groundwater table and is, consequently, connected to the atmosphere. When the organic matter content of the soil is limited, the water does not lose its oxygen (i.e., become anaerobic). As a result, no anaerobic reactions (e.g., iron dissolution) occur in the soil.

In special cases aerobic groundwater meets the requirements for drinking water.
In the Netherlands a couple of groundwater abstraction facilities are located on the Veluwe from which the abstracted water is directly distributed as drinking water. Normally, some treatment is necessary or desired.
Despite the fact that we are dealing with aerobic (i.e., containing oxygen) groundwater, the first treatment step is an aeration phase. Because of this aeration phase, the concentration of oxygen is increased further and the concentration of carbon dioxide is decreased. If the water complies with the legal standards after this treatment step, then the water can be distributed.

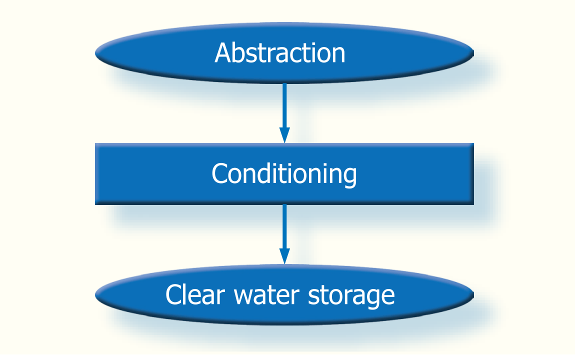


Figure 3 - Treatment of phreatic aerobic groundwater

In the case of aerobic phreatic groundwater, only the parameters pH, Ca, SI and HCO_3^- have to be taken into account. The other parameters generally comply with the legal requirements.
Therefore, the treatment scheme of phreatic aerobic groundwater includes, in addition to a possible aeration, conditioning (Figure 3).

Aggressive water

When aerobic groundwater is abstracted from sandy soils (no calcium in the underground), the groundwater is often aggressive to limestone.
Because of a number of breakdown processes, carbon dioxide is present in groundwater, and, because the calcium is missing, the concentration of carbon dioxide is higher than the equilibrium concentration of carbon dioxide. The value of the saturation index, SI, is smaller than 0. To make distribution of this water possible, the saturation index has to be increased.

The SI is increased by aerating the water, which removes carbon dioxide. Then the SI may meet the requirements, but the requirements for pH and HCO_3^- buffering are often not met because the concentration of HCO_3^- is too low. When limestone (marble) filtration is applied, the requirements for SI, pH and HCO_3^- buffering are met. During limestone filtration, the aggressive water is filtered through a filter bed consisting of marble grains (limestone)

Figure 4 - Aeration above limestone filter

(Figure 4). Because the water is aggressive, it dissolves the marble grains. After some time, the filter bed has to be refilled with new grains.

Hard water

Aerobic groundwater, if abstracted from soils rich in calcium (for example, limestone area of Zuid-Limburg), is often very hard (>3 mmol/l). Because of the biological processes in the soil, the concentration of CO_2 can result in a substantial dissolution of limestone, forming Ca^{2+} and HCO_3^- in the water. The abstracted water, therefore, will be hard.

Groundwater will sometimes be in equilibrium regarding calcium carbonate (limestone). Water that is supersaturated with respect to calcium carbonate cannot be found in nature; because of the long residence time, a possible supersaturation would already have disappeared due to precipitation. When this water is pumped up and comes in contact with air, the carbon dioxide disappears from the water. The carbon dioxide concentration is, after all, larger than the saturation concentration of carbon dioxide in water being in equilibrium with air. Because of the removal of carbon dioxide from the water, the water becomes supersaturated with respect to calcium carbonate (SI > 0).

To prevent limestone precipitation in a distribution network or in consumers' washing machines and heaters, and to satisfy the recommendation of a maximum hardness of 1.5 mmol/l, the water is softened. This softening occurs by dosing chemicals (NaOH or $Ca(OH)_2$) into the water in cylindrical reactors with upward flow (Figure 5). These reactors contain small sand grains, which are used as crystallization nuclei on which the $CaCO_3$ precipitates.

The softening installation should be followed by granular media filtration, because possible post-precipitation might occur. After all, the time the water stays in the pellet reactor is short (a couple of minutes), and for the complete process of chemical softening more time is needed. When, after the softening, a granular media filtration phase is executed, post-precipitation takes place in the filter bed. If this filtration phase isn't provided, then the precipitation will take place in the distribution network or in the consumers' household machines.
Alternatively, acid neutralization can be applied.

Example

As an example of the change in water quality, the Hoenderloo pumping station on the Veluwe is described. Treatment at the Hoenderloo pumping station consists of aeration/gas transfer followed by limestone filtration. The values of the different parameters in Table 1 are the annual averages.

Figure 5 - Pellet reactor for softening water in Meersen (Limburg)

Table 1 - Quality data of the raw and treated water at the Hoenderloo pumping station (Gelderland)

Parameter	Unit	Raw water	Clear water
Temperature	°C	9.6	10
pH	-	6.1	7.8
EGV	mS/m	9.3	14.3
SI	-	-3.4	-0.3
Turbidity	FTU	-	< 0.1
Na^+	mg/l	8.1	7.9
K^+	mg/l	1	1
Ca^{2+}	mg/l	8.6	22.5
Mg^{2+}	mg/l	1.6	1.6
Cl^-	mg/l	12	12
HCO_3^-	mg/l	21	63
SO_4^{2-}	mg/l	9	10
NO_3^-	mg/l	2.7	2.7
O_2	mg/l	4.2	8
CH_4	mg/l	-	-
CO_2	mg/l	31	2
Fe^{2+}	mg/l	0.06	0.03
Mn^{2+}	mg/l	0.02	< 0.01
NH_4^+	mg/l	< 0.04	< 0.04
DOC	mg/l	< 0.2	< 0.2
E.coli	n/100 ml	0	0
Bentazon	µg/l	-	-
Chloroform	µg/l	-	-
Bromate	µg/l	-	-

The pH of the treated water is higher than the raw water, because the water is aerated (removal of CO_2) and because the water is filtered through a limestone filter (decrease in the CO_2 concentration, increase in the HCO_3^- and the Ca^{2+} concentration). The SI increases under the influence of the lower concentration of CO_2, and the higher HCO_3^-, and the Ca^{2+} concentrations; the water becomes less aggressive with respect to calcium carbonate.

Because of the use of limestone filtration, the HCO_3^- and the Ca^{2+} concentrations will increase. More ions will get into the water, as a result of which the conductivity (EC) will increase.

We can calculate the increase in the HCO_3^- concentration when we assume that all produced HCO_3^- comes from the limestone. For every formed mmol/l Ca^{2+}, 2 mmol/l HCO_3^- are produced. At this pumping station the Ca^{2+} -concentration increases with 0.3475 mmol/l because of the limestone filtration, and the concentration of HCO_3^- has to be increased by $2 \cdot 0.3475 = 0.695$ mmol/l. There was 0.34 mmol/l HCO_3^- present in the raw water and thus, there has to be $0.695 + 0.34 = 1.035$ mmol/l HCO_3^- in the treated water. This corresponds to 63.1 mg/l.

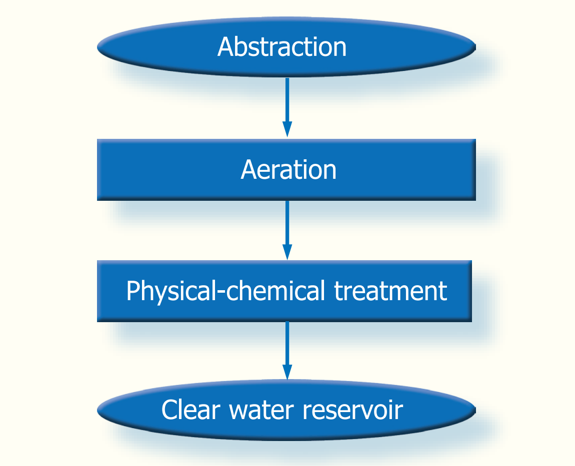


Figure 6 - Treatment of slightly anaerobic groundwater

2.3 Slightly anaerobic groundwater

Slightly anaerobic groundwater is found when the groundwater is located under a confining layer, and is characterized by the lack of oxygen and the presence of ammonium, iron and manganese.

The treatment of slightly anaerobic groundwater often consists of aeration followed by submerged granular media filtration (Figures 6 and 7).

Aeration is necessary for the addition of oxygen and the removal of carbon dioxide. The oxygen is used for the oxidation of Fe^{2+} to Fe^{3+} (a chemical process), and it is also needed for the oxidation of NH_4^+ to NO_3^- and of Mn^{2+} to MnO_2.

Aeration is followed by submerged sand filtration. In the filter the oxidized ferric iron reacts with OH^+-

Figure 7 - Treatment of slightly anaerobic groundwater

ions and is transformed into $Fe(OH)_3$-flocs, which are filtered in the sand bed (a physical process). Manganese undergoes a partly chemical and partly biological transformation, while ammonium is biologically transformed. The transformation of ammonium is accomplished by the bacteria *Nitrosomonas* and *Nitrobacter*. During this transformation a lot of oxygen is used; per mg/l ammonium, the oxygen consumed is 3.55 mg/l. Also, a lot of nitrate is formed; per mg/l ammonium, 3.44 mg/l nitrate is produced.

As a result of the biological transformation of ammonium and manganese and the physical removal of the iron hydroxide flocs, the pore volume between the sand grains decreases, because the pores are filled by either bacteria or by flocs and deposits. The result of this is the increase in the hydraulic resistance of the water when flowing through the filter bed. When this resistance becomes too large, the filter should be backwashed.

Example

As an example of the change in water quality of slightly anaerobic water, the pumping station at the Zutphenseweg will be described. The treatment at the Zutphenseweg pumping station consists of aeration/gas transfer followed by sand filtration and a second aeration. The values of the different parameters in Table 2 are the average values over a year. As a result of aeration the concentration of CO_2 will decrease and the pH of the water will increase. Because of aeration the concentration of oxygen will increase to a value near the saturation value (ca. 10 mg/l). The concentration of Fe^{2+}, Mn^{2+} and NH_4^+ will decrease due to the influence of oxidation and biological transformations. The nitrate content will increase, because the ammonium is transformed into nitrate. Since the decrease in ammonium is approximately 0.8 mg/l, the nitrate content should increase circa 2.7 mg/l. The oxygen consumption is approximately 2.8 mg/l. To get a high oxygen content, post-aeration is used.

Table 2 - Quality data of the raw and treated water at Zutphenseweg pumping station (Overijssel)

Parameter	Unit	Raw water	Clear water
Temperature	°C	13.1	13.1
pH	-	7.7	7.9
EGV	mS/m	58	58
SI	-	-0.1	0.1
Turbidity	FTU	-	< 0.1
Na^+	mg/l	75	75
K^+	mg/l	6.7	6.7
Ca^{2+}	mg/l	47	46
Mg^{2+}	mg/l	7.8	8
Cl^-	mg/l	108	110
HCO_3^-	mg/l	185	177
SO_4^{2-}	mg/l	< 1	< 1
NO_3^-	mg/l	< 0.1	2.8
O_2	mg/l	0.4	9.5
CH_4	mg/l	-	-
CO_2	mg/l	7	4
Fe^{2+}	mg/l	0.39	0.03
Mn^{2+}	mg/l	0.03	< 0.01
NH_4^+	mg/l	0.82	< 0.04
DOC	mg/l	2	1,7
E.coli	n/100 ml	0	0
Bentazon	µg/l	-	-
Chloroform	µg/l	-	-
Bromate	µg/l	-	-

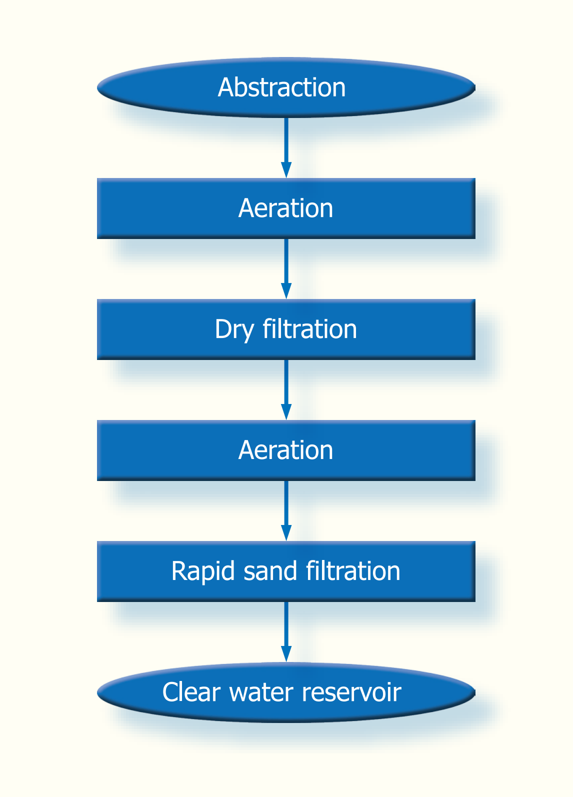


Figure 8 - Treatment of deep anaerobic groundwater

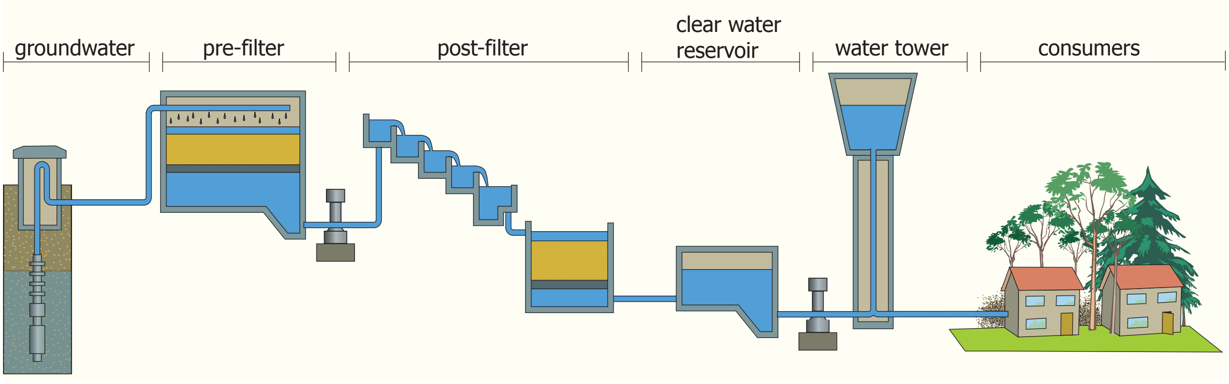


Figure 9 - Treatment of groundwater with double aeration/filtration

2.4 Deep anaerobic groundwater

Deep anaerobic groundwater is found when the water is abstracted under a confining layer and no oxygen is present in the water. Furthermore, there is no nitrate present and organic material is broken down with sulfate as an oxidant. Iron, manganese and especially ammonium are present in high concentrations, while hydrogen sulfide and methane are also present in the groundwater.

During the removal of ammonium, a lot of oxygen is used. When the ammonium content is larger than 3 mg/l, the amount of oxygen necessary for the removal of the ammonium is greater than the total amount of oxygen, which can be dissolved in water (saturation concentration). To prevent anaerobic conditions in the last filter, double submerged filtration or dry filtration followed by submerged filtration is used during groundwater treatment with a high amount of ammonium.

Dry filtration is followed by submerged filtration because in a dry filter, the breakthrough of particles may occur. When these materials pass through the dry filter, they are filtered in the submerged filter and do not show up in the drinking water.

An aeration phase is present before every filtration step, so the oxygen concentration is high before the water enters the filter and the carbon dioxide is removed (Figures 8 and 9). A dry filter is a filter filled with sand grains with a diameter between 0.8 and 4 mm. A layer of water is not present in the filter, like with submerged filtration. In the dry filter the water flows down past the grains, at the same time air is flowing with the water. The oxygen in the air replenishes the oxygen in the water, which is used by bacteria. In this way more than 3 mg/l of ammonium can be transformed without anaerobic results in the filter.

Example

As an example of the change in water quality of deep anaerobic groundwater, the St. Jansklooster pumping station is described. The treatment at this pumping station consists of aeration, dry filtration,

Table 3 - Quality data of the raw and treated water at St. Jansklooster pumping station (Overijssel)

Parameter	Unit	Raw water	Clear water
Temperature	°C	10.5	10.5
pH	-	6.9	7.6
EGV	mS/m	51	48
SI	-	-0.4	0.2
Turbidity	FTU	-	< 0.1
Na^+	mg/l	23	21
K^+	mg/l	3	3
Ca^{2+}	mg/l	82	77
Mg^{2+}	mg/l	5.2	6.3
Cl^-	mg/l	41	41
HCO_3^-	mg/l	267	241
SO_4^{2-}	mg/l	18	21
NO_3^-	mg/l	0.07	1.6
O_2	mg/l	0	10.7
CH_4	mg/l	2	< 0.05
CO_2	mg/l	63	11
Fe^{2+}	mg/l	8.8	0.04
Mn^{2+}	mg/l	0.3	< 0.01
NH_4^+	mg/l	2.2	< 0.01
DOC	mg/l	7	6
E.coli	n/100 ml	0	0
Bentazon	µg/l	-	-
Chloroform	µg/l	-	-
Bromate	µg/l	-	-

aeration and submerged filtration. The values of the different parameters in Table 3 are the average values over a year.
As a result of the aeration phases, the amount of carbon dioxide will decrease and the pH will increase. Furthermore, the amount of oxygen will increase. The concentration of Fe^{2+}, Mn^{2+} and NH_4^+ will decrease because of chemical and biological transformations; the amount of nitrate, on the other hand, will increase. The concentration of nitrate increases less than the theoretical calculation.

3. Riverbank groundwater

3.1 *Types of riverbank groundwater*

Riverbank filtration is groundwater abstracted directly adjacent to surface water, usually from a river. The abstraction takes place in such a way that the abstracted water consists mostly of surface water. This surface water is infiltrated into the soil via the riverbank or the river bottom. In this way, a mixture of surface water and natural groundwater is abstracted.

The residence time of the infiltrated surface water in the soil can be several years. In this case we call it riverbank groundwater. This groundwater has the characteristics of groundwater, but the chemical composition also reveals surface water. In the Netherlands such abstractions are found along the Lek and the IJssel. The distance between abstraction wells and the river vary between 200 and 1,000 m.

Figure 10 - Riverbank groundwater well in Germany

In Germany most abstraction wells are placed much closer to the river (Figure 10). Residence times of several weeks are common. It is then called riverbank filtrate. It is clear that the existence of surface water in such cases is easier to recognize. A well-defined boundary between riverbank groundwater and riverbank filtrate doesn't exist.

3.2 *Riverbank groundwater*

The treatment of riverbank groundwater has many similarities to the treatment of slightly anaerobic groundwater. Riverbank groundwater is, for the most part, "natural" groundwater. The other part is surface water that has some of the characteristics

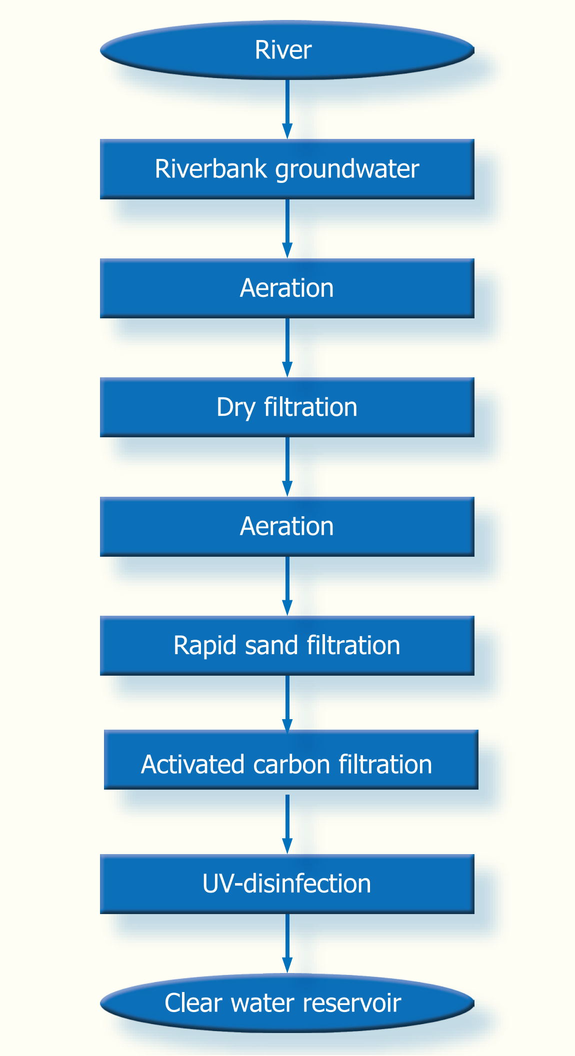


Figure 11 - Treatment of riverbank groundwater

Figure 12 - Aeration over a dry filter in Zwijndrecht (Zuid-Holland)

of groundwater due to a long residence time in the soil.

The treatment scheme for riverbank groundwater is shown in Figure 11. Depending on the soil composition, higher concentrations of iron, ammonium, manganese and methane can be found. Furthermore, the hardness can be fairly high because of infiltration of river water. Due to high concentrations of ammonium, which are biologically transformed to nitrate, a lack of oxygen can occur in the treatment; therefore, an extra dry filtration stage is often included (Figure 12).

Activated carbon filtration is also used for the treatment of riverbank groundwater because of taste problems and problems with pesticides. Because part of the water is surface water, it also contains substances associated with surface water.

For riverbank groundwater, UV-disinfection is often applied as the last disinfection stage, especially if activated carbon filtration is used in the treatment. In the activated carbon filters, microorganisms grow due to the breakdown of organic material; these can subsequently end up in the water.
With UV-disinfection the microorganisms are killed, without the formation of disinfection by-products which are typical for chemical disinfection.

Example
As an example of riverbank groundwater, the Nieuw-Lekkerland pumping station of Hydron Zuid-Holland is described. Table 4 shows that the water contains a high concentration of ammonium and that there are pesticides present in the water.
Hence, the treatment scheme is as follows: aeration, dry filtration, aeration, submerged filtration, activated carbon filtration, and UV-disinfection.

Chloride can become a problem for riverbank groundwater treatment plants along the Rhine. In the treatment, chloride isn't removed. When the concentration in the Rhine is too high, then the standard for chloride may be exceeded.

Oxygen increases because of the aeration steps. Manganese and iron decrease because of the combination of aeration and filtration. Ammonium decreases because of transformation in the dry and submerged filters. Because of that, the nitrate

Table 4 - Quality data of raw and treated water at Nieuw-Lekkerland pumping station (Zuid-Holland)

Parameter	Unit	Raw water	Clear water
Temperature	°C	12	12
pH	-	7.3	7.4
EC	mS/m	78.4	77
SI	-	-0.2	-0.1
Turbidity	FTU	-	< 0.1
Na^+	mg/l	69	70
K^+	mg/l	4	4
Ca^{2+}	mg/l	84	84
Mg^{2+}	mg/l	12	12
Cl^-	mg/l	128	135
HCO_3^-	mg/l	223	187
SO_4^{2-}	mg/l	55	59
NO_3^-	mg/l	< 0.1	2.3
O_2	mg/l	0.8	5.7
CH_4	mg/l	1	< 0.05
CO_2	mg/l	20	14
Fe^{2+}	mg/l	3.8	0.02
Mn^{2+}	mg/l	0.9	< 0.01
NH_4^+	mg/l	3	< 0.03
DOC	mg/l	3	2.5
E.coli	n/100 ml	0	0
Bentazon	μg/l	0.32	< 0.05
Chloroform	μg/l	-	-
Bromate	μg/l	-	-

content increases. Because of activated carbon filtration, the Bentazon content decreases.

There are no E.coli in the raw water because the raw water passes through the soil. During UV-disinfection, possible organisms are killed that grow in the activated carbon filter.

3.3 Riverbank filtrate

The treatment of riverbank filtrate doesn't show many differences from the treatment of riverbank groundwater. Only in this case, the share of surface water is larger, which makes activated carbon filtration and post-UV-disinfection more important.

Dosing with ozone is applied in a number of cases for riverbank filtrate, oxidizing the micropollutants.

Dosing with ozone is, in this case, not necessary for disinfection. When the water is passing through the soil, all (harmful) bacteria are removed, even with a relatively short residence time.

For soil passage the filtration of microorganisms is the most important removal mechanism. For this, reference is made to the good microbiological water quality, obtained with slow sand filtration in surface water treatment. In a slow sand filter, good disinfection is obtained with a residence time of only 0.5 - 1.0 days.

4. Surface water with direct treatment

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.

In order to be suitable for drinking water, suspended solids must be removed together with pathogenic bacteria. Over the years the removal of micropollutants has become necessary as well, together with the construction of storage basins, to used when the concentration of micropollutants is too high. Micropollutants often originate from human activities upstream.

The next section will describe the historical development of the direct treatment of surface water. Then, the contemporary treatment schemes will be described, followed by a description of future treatment schemes. Finally, the individual treatment processes in those schemes will be explained.

4.1 Historical developments

Throughout the ages, because of the increasing quantitative demand (due to population growth and consumption growth) and the increasing qualitative demand (because of worse sources and 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, making an increased production capacity with traditional means possible. To guarantee the bacteriological quality of the drinking water, a safety chlorination was applied as a final step in the treatment process. This caused a small amount of chlorine to be present in the water at the customers' taps.

In time, production needed to be increased further. This caused the rapid filtration system to be heavily loaded, resulting in run times that were too short between backwashing. The problem was solved by adding a flocculant before sedimentation, thus increasing the effectiveness of the sedimentation step.

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) bacteria as well. Slow sand filtration was increasingly replaced by chemical disinfection (e.g., break-point chlorination). Break-point chlorination oxidizes ammonium (NH_4^+) to nitrogen (N_2) as well.

Increased river contamination necessitated the construction of reservoirs to be able to stop the direct intake of river water. Additionally, micropollutants needed to be removed by activated carbon (i.e., dosing of powdered activated carbon, PAC). This traditional treatment process (Figure 13) is still widely applied around the world.

The reservoirs were shallow basins at first. In these shallow reservoirs however, a considerable algal population can develop during spring and summer.
The first step in the treatment process is the application of microstrainers because of this algal bloom. Algae are quite difficult to remove by way of sedimentation, which is, in fact, only possible when using very high doses of flocculants. Additionally, algae can cause taste and odor problems.
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 will yield 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 flocculant followed by rapid sand filtration can be used.

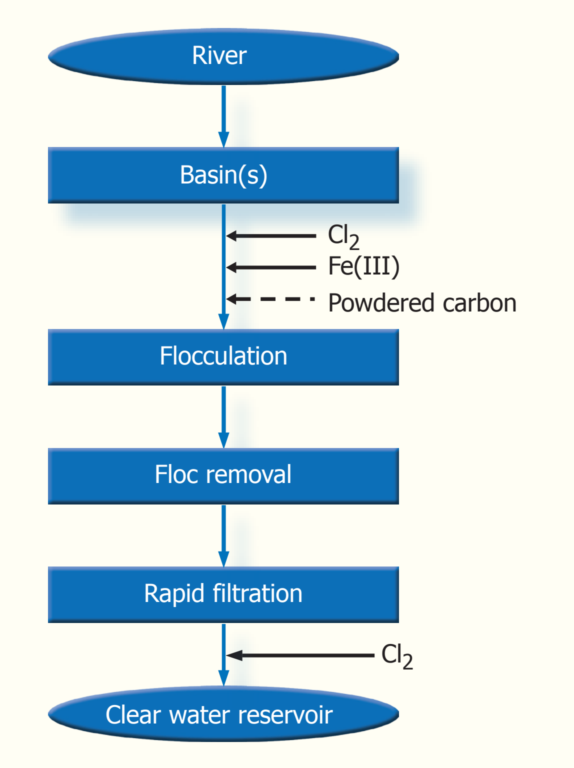


Figure 13 - Tratitional treatment scheme for direct treatment of surface water

4.2 Contemporary treatment

Problems with traditional treatment
Contemporary treatment originated from the chlorination issue and the increased river water pollution. 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 exceedence of this standard; but without sufficient chlorination, the disinfection would be inadequate, a worse condition from the point of view of public health. This caused the Dutch Decree to temporarily allow a THM value to 100 μg/l (until January 1, 2006).

In 1987 the insecticide Bentazon was found in Amsterdam's drinking water. Like many micropollutants, this insecticide proved to be insufficiently removed in the treatment process, even in the case of artificial infiltration into sand dunes. Other insecticides, like Atrazin and Diuron, have also been shown to pass through a traditional treatment process. Because activated carbon filtration does remove these pollutants sufficiently, it has become a typical step in any contemporary treatment process.

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*. Using higher doses and longer contact times will 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.

Characteristics of temporary direct treatment
Characteristics of the current treatment of surface water for production of drinking water are:

- 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 significant self-purification (sedimentation of suspended solids, ammonium oxidation) while still keeping algae growth under control
- removal of suspended solids by coagulation (adding flocculants), flocculation and floc removal by filtration, possibly preceded by sedimentation or flotation
- primary disinfection using a minimal amount of chlorine or ozone
- removal of micropollutants by activated carbon filtration
- secondary disinfection using a minimal amount of chlorine or chlorine dioxide

Example of contemporary direct treatment (chlorine and activated carbon filtration)
An example of current direct treatment can be found at the Berenplaat production plant (Figures 14 and 15).
At this site drinking water is produced from Meuse water, which has first been stored in the Biesbosch storage reservoirs. At the Berenplaat plant, microstrainers form the first step in the treatment scheme. This process was selected because, previously, the water, stored in a shallow basin, led to algae growth. In the current scheme the microstrainers could have been omitted, but, actually, they have been left in service.

To disinfect the water, hypochlorite is added (about 1 mg/l as Cl_2). This needs to contact the water for half an hour, which happens 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

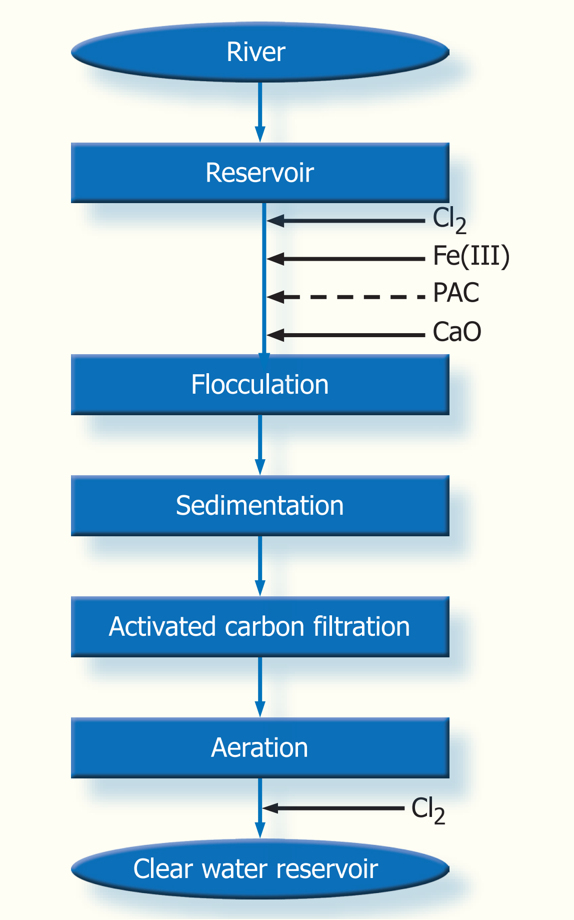


Figure 14 - Contemporary direct treatment of surface water (Berenplaat, before 2006)

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 adding of $FeCl_3$ is for removing 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.

Because the flocs are heavier than water, they can be removed by sedimentation. This is done in the floc-blanket clarifier (floc removal). 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.

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.

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

Cascades (five steps with a total height of about 2 meters) bring oxygen into the water; before that

Figure 15 - Drinking water production at the Berenplaat production plant (Zuid-Holland)

Table 5 - 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

water is pumped into the clear water reservoirs. Aeration is included in the treatment process in order to add oxygen which could be low in the raw water because of biological processes. Chlorine dosing causes the biological activity during the treatment process to be minimal.
Hypochlorite is added before the clear water reservoirs (ca. 0.5 mg/l as Cl_2) to prevent regrowth during transportation.

The data shown in Table 5 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. By forming $Fe(OH)_3$ 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 causes an increased chloroform concentration and a reduced E.coli number.

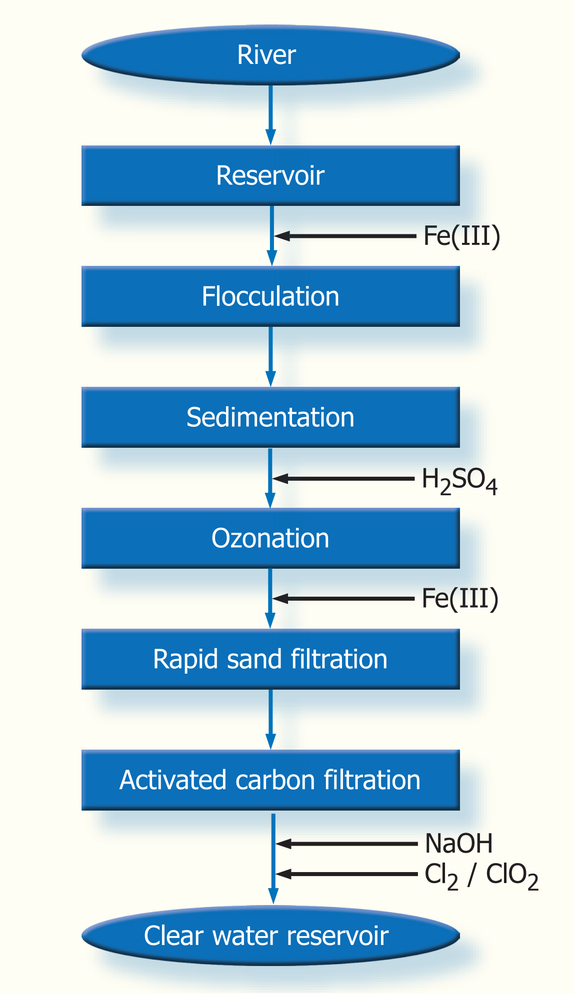


Figure 16 - Contemporary direct treatment of surface water with ozonation

Example of contemporary direct treatment (ozone with activated carbon filtration)

Another example of contemporary treatment is found at the Kralingen production plant (Figures 16 and 17). Here, drinking water is also produced from Meuse water from the Biesbosch reservoirs. At the Kralingen plant a flocculant is added first (ca. 4 mg/l Fe^{3+} in the form of $FeCl_3$), before the water goes through a static mixer. This causes small $Fe(OH)_3$ flocs to form and to include pollutants from the water. If necessary, another 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 cause the flocs to grow. The mixing decreases in intensity in each consecutive compartment in order to prevent flocs from being destroyed. The flocs are removed in a lamella

Figure 17 - Kralingen drinking water production plant

separator where they settle between ascending 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 flocculation and floc removal, sulfuric acid is added first to lower the pH, because ozone is more effective at low pH values. Ozone is produced locally from liquid oxygen. In ozone generators the oxygen is exposed to high electric voltages, thus creating ozone. By means of a diffuser, the 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. The ozone gas that is released at the water's surface is destroyed thermally. Ozone kills bacteria and viruses, destroys micropollutants, and improves 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, first an extra flocculant 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 anthracite layer of 0.8 m. Below these layers there is a gravel support layer. The filtration rate is a maximum of 20 m/h. Because the filters clog, they are backwashed 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. The remaining micropollutants and the taste and odor compounds are removed. Because the activated carbon activity decreases in time, it needs to be reactivated every 1 - 2 years. Also, 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.

Table 6 - 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

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

Table 6 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.

Mainly, the concentrations of DOC and Bentazon are reduced during the activated carbon filtration. With ozone, the increased retention time, and the greater biological activity, DOC removal is better at Kralingen than at the Berenplaat production plant. The low chlorine dosing results in a small increase in chloroform in the water.

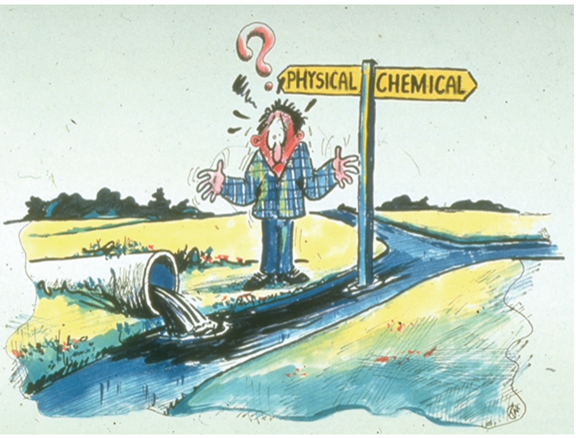


Figure 18 - Future treatment of surface water: physical or chemical

4.3 Future treatment

Problems of contemporary treatment

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.

The effective removal of *Cryptosporidium* and *Giardia* requires 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 require an oxidation process with high doses, which will again give rise to the formation of undesirable by-products.

Also, the increase of hormones in surface water (e.g., 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.

The above developments require 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 18).

Figure 19 - UV disinfection (right) followed by activated carbon filtration (left) at Berenplaat production plant (Zuid-Holland)

Biological processes

In biological processes, many pollutants are assimilated by biomass and removed in this way. Also, biological processes will 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 will be low and residual disinfection will be unnecessary.

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

- biologically activated carbon filtration
- slow sand filtration

For Amsterdam's water supply some steps in this direction have been taken in recent years, and some aspects of it are currently operational. Further optimization of the contemporary treatment processes is being researched.

Physical processes

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

- UV disinfection (Figure 19)
- membrane filtration

By exposing the water to UV radiation, the DNA structure of organisms is destroyed, thereby stopping growth. It has proved 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

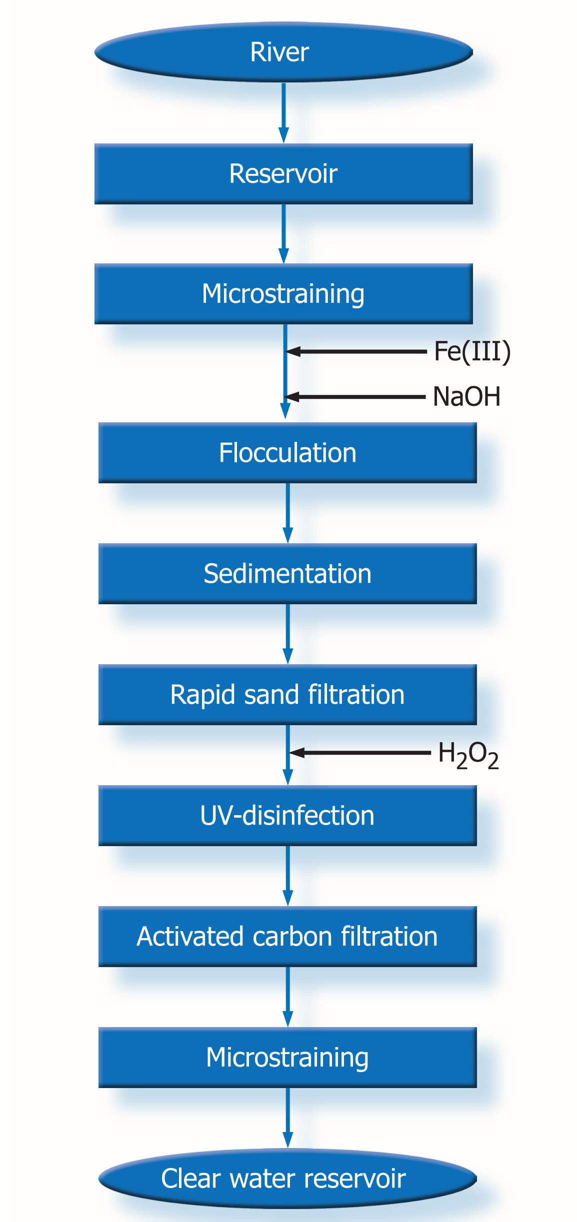


Figure 20 - Direct treatment of surface water at Andijk production plant (2005)

Figure 21 - UV / H_2O_2 (Andijk)

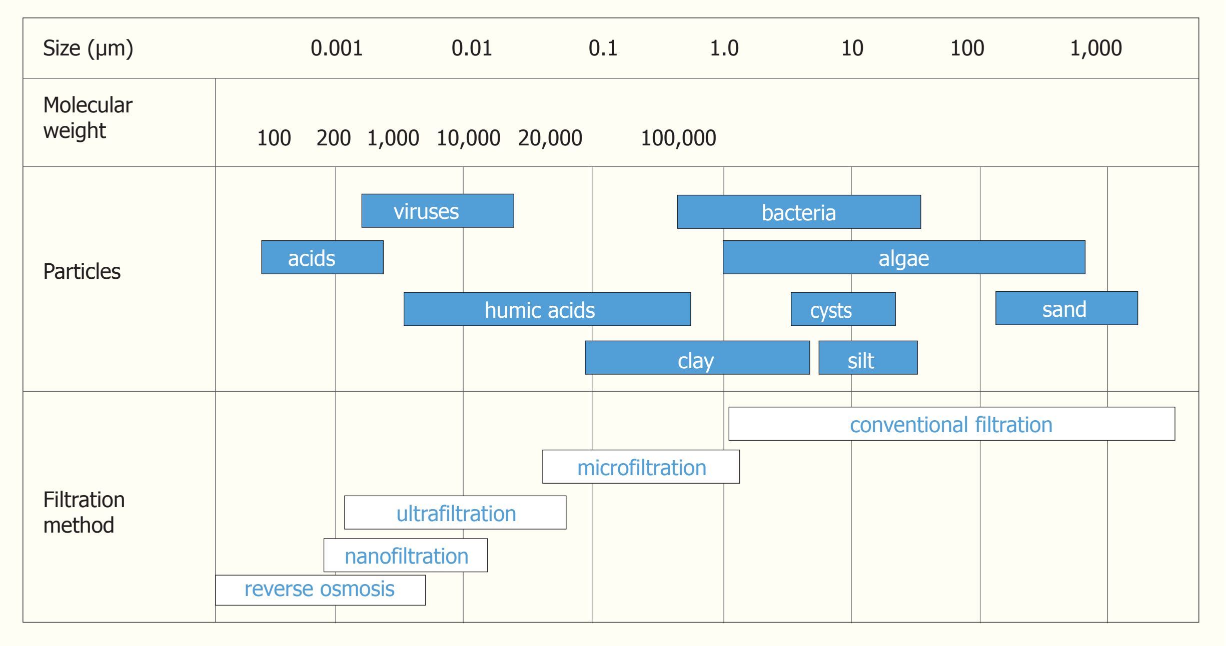


Figure 22 - Application fields for membrane filtration

example of such a system is the Noord-Holland (Andijk) water supply (Figures 20 and 21).

With membrane filtration, the water is pressurized through a membrane. These membranes are available in several different pore sizes (Figure 22).

Ultra- and microfiltration mainly retain the coarser pollutants, like suspended solids, cysts and bacteria. Nanofiltration also retains divalent ions (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 23 and 24) was started up in Noord-Holland

Figure 23 - Membrane filtration plant in Heemskerek (Noord-Holland)

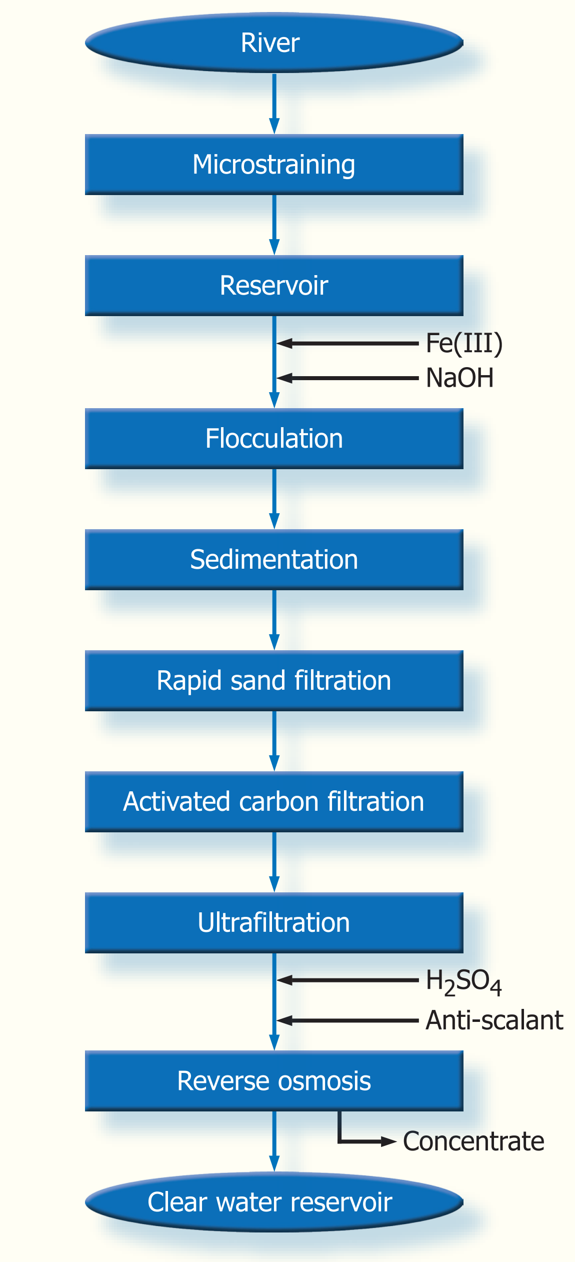


Figure 24 - Direct treatment of surface water at Heemskerk production plant

(Wijk aan Zee). The produced water is mixed with drinking water from a system of artificially infiltrated surface water.

5. Surface water with infiltration

5.1 Surface water with open infiltration

The source of infiltration water is surface water. However, the disadvantages of surface water include a temperature and salinity vary throughout the year, contamination from pathogenic micro-organisms, and the possibility that, even after treatment, the growth and settling of particles in the distribution network may occur.

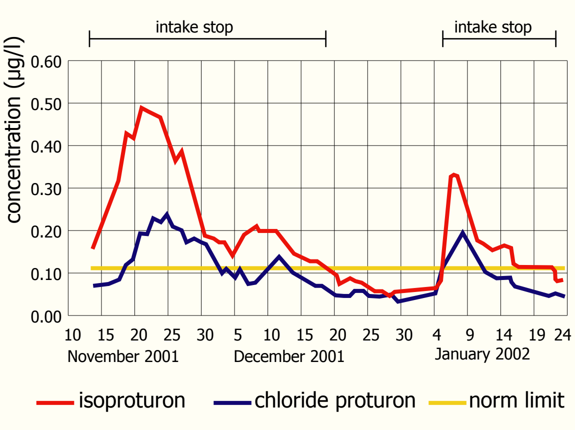


Figure 25 - Pollution at the intake point of the WRK Nieuwegein

By infiltrating the surface water into the ground, its quality is improved. This means that the pathogenic microorganisms are degraded and that the water is in a better biological and chemical state, causing no settling and no regrowth to occur.
Also, the temperature changes are levelled. Both the temperature and the salinity will be more or less constant.

Water can be infiltrated into freatic groundwater. When the supply of treated surface water is obstructed somehow (e.g., accident, network repair), it is possible to continue the abstraction for some time. During this time the groundwater level decreases, but this is, to some extent, acceptable without damaging the natural biology.

Infiltration projects cover large areas that also need to be protected, because they mainly deal with large amounts of water. However, as the infiltration area is always developed as a natural area, it will have a high recreational value.

Figure 25 shows an example of an intake stop because of contamination of the surface water by insecticides. Because the contamination occurred in winter, an intake stop of some weeks could be taken without damaging the environment in the infiltration area.

5.2 Surface water with deep infiltration

Expansion of natural infiltration into the dunes is not always possible because of environmental aspects. A water company using water from the dunes has, nevertheless, two possibilities to increase capacity.

First, the pre-treated surface water can be purified directly (see direct treatment), after which the water is mixed with the infiltrated water.

Second, the company may apply deep infiltration. Deep infiltration infiltrates the water into a confined aquifer. Because of the enclosing clay layers, there is almost no exchange with the freatic water above, so the infiltrated water does not influence the ecosystem.

aWhen using deep infiltration, care has to be taken during the preliminary treatment. The fewer particles that are present in the water, the smaller the chance that the infiltration wells will clog. Storage in deep infiltration is limited. When extracting water without supplying the necessary water for a long period, the chance of salt water intrusion exists.

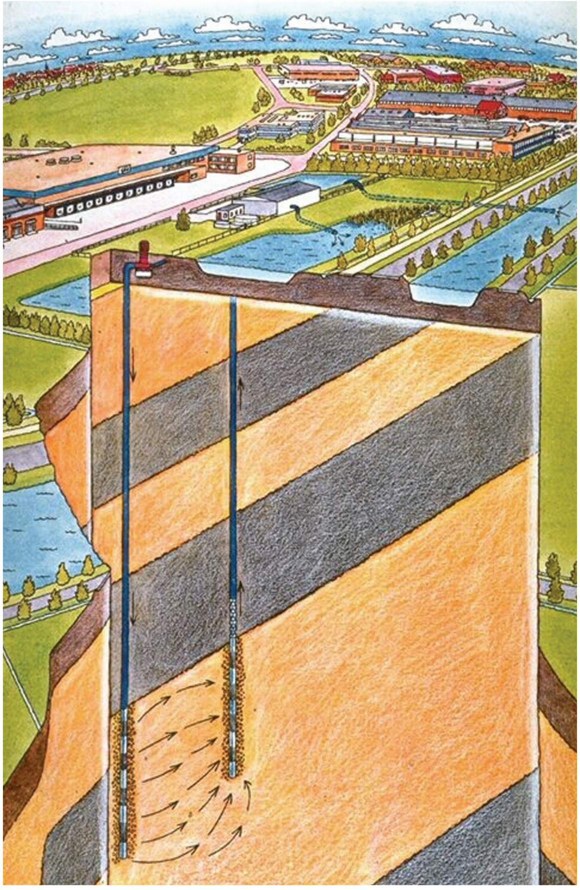


Figure 26 - Deep infiltration at Someren (Noord Brabant)

Deep infiltration is not pursued only in the dunes. Also in other parts of the Netherlands, deep infiltration is used for the production of drinking water (Figure 26). The requirements are that the soil is sufficiently permeable and that there are confining layers in the underground.

5.3 Pre-treatment

To make the surface water suitable for transport and infiltration, suspended particles need to be removed first.

The standard pre-treatment of surface water consists of flocculation followed by floc removal and rapid filtration (Figure 27).

Flocculation is achieved by adding a flocculant, which removes the negative charge of the colloid particles, thereby making flocculation possible. These flocs can be removed by means of sedimentation in large ponds or in compact lamella separators, or by means of flotation.

Not all flocs are removed during sedimentation. Small flocs remain suspended and need to be removed by means of rapid filtration.

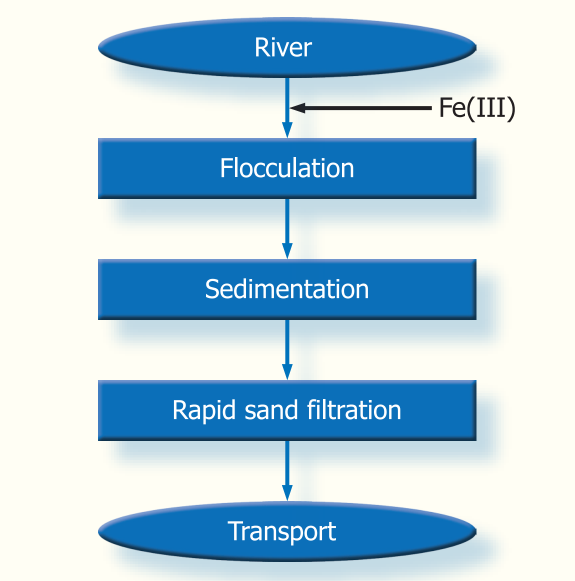


Figure 27 - Preliminary treatment of surface water for infiltration

Table 7 - Quality data of the raw and treated water at Nieuwegein (Utrecht)

Parameter	Unit	Raw water	Clear water
Temperature	°C	12.5	12.5
pH	-	8	7.8
EC	mS/m	80	80
SI	-	0.4	0.2
Turbidity	FTU	10.4	0.2
Na^+	mg/l	80	81
K^+	mg/l	6	6
Ca^{2+}	mg/l	81	81
Mg^{2+}	mg/l	11	11
Cl^-	mg/l	149	155
HCO_3^-	mg/l	157	156
SO_4^{2-}	mg/l	66	67
NO_3^-	mg/l	4	4
O_2	mg/l	9.2	7.3
CH_4	mg/l	-	-
CO_2	mg/l	2.6	4.4
Fe^{2+}	mg/l	-	-
Mn^{2+}	mg/l	-	-
NH_4^+	mg/l	-	-
DOC	mg/l	3.9	3
E.coli	n/100 ml	5,000	50
Bentazon	µg/l	0.2	0.2
Chloroform	µg/l	0	0
Bromate	µg/l	< 2.0	< 2.0

In the flocs, many other materials are removed like heavy metals (being positively charged and adsorbed to the flocs), and microorganisms. As a flocculant, mostly a trivalent metal salt, like iron chloride ($FeCl_3$), iron chloride sulfate, or aluminum sulfate, is used.

At the WRK Nieuwegein production plant (NV Watertransportmaatschappij Rijn-Kennemerland), flocculation is accomplished with iron chloride, followed by settling in a large sedimentation tank, and rapid filtration (Figure 27 and 28, Table 7).

Figure 28 - Open sedimentation pond at Nieuwegein (Utrecht)

The quality of surface water varies throughout the year. For example, the turbidity at the Nieuwegein site varies between 5.5 and 25.5 FTU and the temperature between 2 and 23°C. This influences the settling behavior, the filtration, and the biological processes.

During the treatment process the composition of the water changes. The quantity of suspended solids, the turbidity, the amount of heavy metals, like cadmium and nickel, and the colony count decrease.

By adding iron chloride, the chloride concentration of the water rises. On average 3 mg/l Fe^{3+} are added, implying an increase in the chloride concentration of 5.7 mg/l. The ferric ions form a compound together with the hydroxide ions, thus removing hydroxide ions and reducing the pH value.

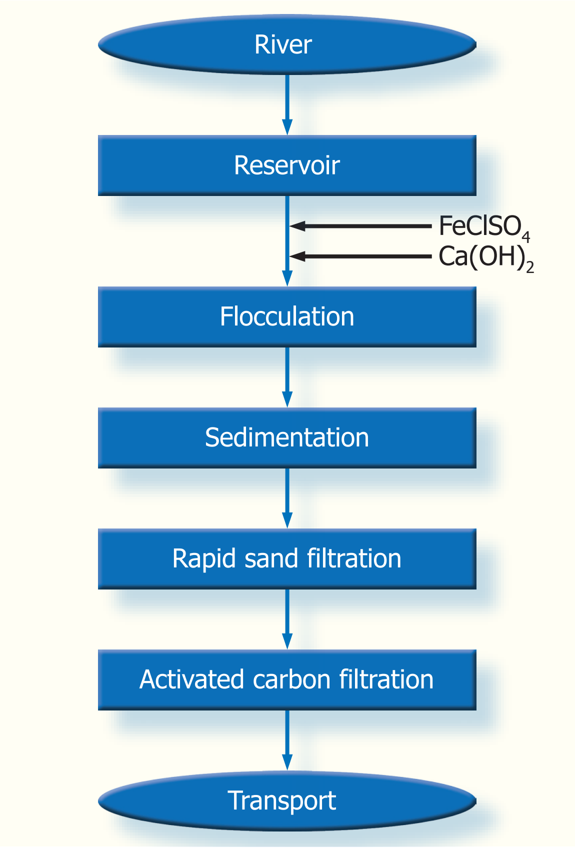


Figure 29 - Treatment scheme of infiltration water where organic micropollutnats are removed

The quality standards for infiltration water have been made stricter.

Originally, preliminary treatment was performed in order to prevent contamination of the transport pipelines and the clogging of the infiltration ponds. Nowadays, another requirement is that no elements foreign to the infiltration environment accumulate (like organic micropollutants). The standard pre-treatment process for infiltration water does not remove organic micropollutants like insecticides. This requires the preliminary treatment process to be expanded with activated carbon filtration (Figure 29).

At the WRK Andijk site, the preliminary treatment process consists of a reservoir, flocculation, floc removal (lamella settling), rapid filtration and activated carbon filtraton. Iron chloride sulfate ($FeClSO_4$) is used as a flocculant.

Growth of algea is common in the IJsselmeer. Therefore, the amount of organic matter (DOC) and the turbidity are high (Table 8). To reduce the algae, the flocculant needs to be added in relatively large amounts, 20 mg/l Fe^{3+} on average. This causes the pH value of the water to decrease. To increase the pH value, lime ($Ca(OH)_2$ is added.

Table 8 - Quality data of the raw and treated water at Andijk (Noord-Holland)

Parameter	Unit	Raw water	Clear water
Temperature	°C	11	11.1
pH	-	7.8	7.8
EC	mS/m	95	80
SI	-	0.1	0.2
Turbidity	FTU	8	0.2
Na^+	mg/l	113	81
K^+	mg/l	9	6
Ca^{2+}	mg/l	70	81
Mg^{2+}	mg/l	14.5	11
Cl^-	mg/l	150	160
HCO_3^-	mg/l	138	115
SO_4^{2-}	mg/l	37	67
NO_3^-	mg/l	4	4
O_2	mg/l	10.1	9.5
CH_4	mg/l	-	-
CO_2	mg/l	2.6	1.3
Fe^{2+}	mg/l	-	-
Mn^{2+}	mg/l	-	-
NH_4^+	mg/l	-	-
DOC	mg/l	8	3.3
E.coli	n/100 ml	5,000	50
Bentazon	µg/l	0.2	< 0.1
Chloroform	µg/l	0	0
Bromate	µg/l	< 2.0	< 2.0

Because WRK Andijk water is now used for both deep infiltration and membrane filtration, the requirements regarding turbidity and the clogging capacity, expressed as MFI (membrane fouling index), have been increased. Those demands may be met by the current treatment process, given that the process is well-controlled.

At WRK Andijk no inexpensive iron chloride nor caustic soda is added, because the IJsselmeer contains large concentrations of chloride and sodium, which should not be further increased.

5.4 Infiltration

Pre-treatment is sited at the intake point of the surface water. This site is rather remote from the infiltration area. Infiltration, therefore, requires long transport pipes.

The pre-treated surface water infiltrates into the soil, which results in a quality improvement, including the levelling of concentrations.

A retention time of two months is deemed enough to make the water reliable, from a microbiological point of view.

The composition of the infiltrated water is different from the composition of the original dune water. Foreign water is infiltrated into the dunes. This will cause nutrients to enter the normally poor sand soil, thus changing the vegetation. In this way infiltration can affect natural areas.

After being abstracted out, the dune water is transported through pipes to the final treatment plant.

5.5 Final treatment of infiltrated water

After being abstracted, the water requires a final treatment.

The soil passage in the dunes removes micro-organisms and, at the same time, iron, manganese, and ammonium ions from the soil are dissolved. These ions need to be removed from the water. In case the water was not treated with activated carbon before infiltration, organic micropollutants

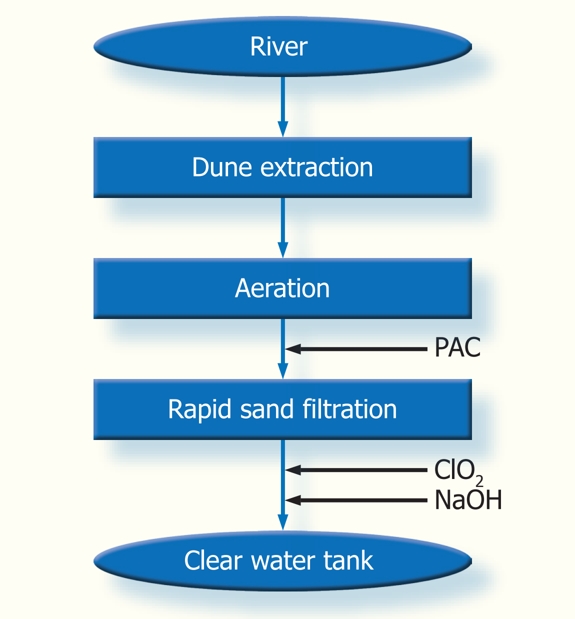


Figure 30 - Quality data of the raw and treated water at Andijk (Noord-Holland)

may be present in the water. Those need to be removed as well.

The simplest procedure for the final treatment of infiltration water is similar to a groundwater treatment plant: aeration followed by rapid filtration (Figure 30).

As an example of the final treatment of infiltration water, the Bergen plant in Noord-Holland is considered.

Pre-treated water from the IJsselmeer (with activated carbon filtration) is infiltrated into the dunes. Abstracting is done by means of a closed system. The final treatment consists of aeration and rapid filtration.

Despite the fact that the hardness of the water is rather high (2.25 mmol/l), no softening process is applied.

The abstracted water has a low turbidity, because it has been filtered by the dunes (Table 9).

During the retention time in the ground, the oxygen concentration is reduced. During the aeration phase the oxygen rate will rise again.

During aeration the iron and manganese ions are oxidized. To remove the iron hydroxide and manganese oxide, rapid filtration is used. The ammonium is transformed into nitrate in the rapid filter.

Table 9 - Quality data of the raw and treated water at Bergen treatment plant

Parameter	Unit	Raw water	Clear water
Temperature	°C	11.7	12
pH	-	7.6	7.7
EC	mS/m	86	86
SI	-	0.1	0.0
Turbidity	FTU	-	0.1
Na^+	mg/l	78	78
K^+	mg/l	7	7
Ca^{2+}	mg/l	89	90
Mg^{2+}	mg/l	13	12
Cl^-	mg/l	147	149
HCO_3^-	mg/l	192	198
SO_4^{2-}	mg/l	92	93
NO_3^-	mg/l	1	1
O_2	mg/l	0.2	8
CH_4	mg/l	0	0
CO_2	mg/l	9	7
Fe^{2+}	mg/l	0.6	0.03
Mn^{2+}	mg/l	0.1	< 0.01
NH_4^+	mg/l	0.31	< 0.03
DOC	mg/l	3	3
E.coli	n/100 ml	0	0
Bentazon	µg/l	< 0.1	< 0.1
Chloroform	µg/l	0	0
Bromate	µg/l	< 2.0	< 2.0

The concentrations of Bentazon and Diuron (pesticides) are low when abstracting water from the dunes. This is because of the activated carbon filtraton before infiltration. The concentrations will not be reduced further during the final treatment phase.

Generally, the applied treatment process is more extensive in practice. This is partly due to the treatment processes chosen in the past. Then, final treatment of infiltrated water consisted of slow sand filtration only. Later, other treatment techniques were added. The slow sand filters are still functional when the abstraction of water is done in an open system. In that case, the slow sand filters remove pathogenic microorganisms.

Infiltration water from the large rivers and from the IJsselmeer has a high hardness. Softening with pellet reactors is undertaken to reduce the hardness to about 1.5 mmol/l. These pellet

Figure 31 - Infiltration area and post-treatment plant near Scheveningen

reactors are used after aeration and before rapid filtration, in order to remove the carry-over.

When they have not been removed during preliminary treatment, organic micropollutants are removed by means of powdered carbon or activated carbon filtration. The addition of powdered carbon is done before weir aeration, because that process will sufficiently mix the powder with the water. When activated carbon filtration is used, it is done after rapid filtration.
To improve the removal of organic micropollutants, ozonation can be used. Ozonation oxidizes organic macro-molecules into smaller organic molecules, which can be removed more easily during activated carbon filtraton. A disadvantage of the combination of ozonation and activated carbon filtration is that there will be a high rate of biological activity in the activated carbon filters. This may cause microorganisms to be present in the water, which will require disinfection after activated carbon filtration. This disinfection is done in the slow sand filters.

All in all this makes for quite an extensive treatment process, especially considering the fact that the water has been pre-treated before infiltration and transported over large distances. Therefore, the price of drinking water prepared from infiltration water is higher than that of water produced from groundwater.