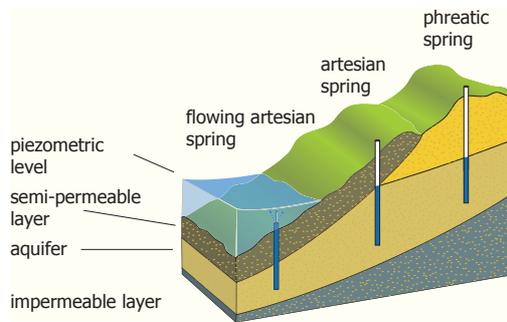


Groundwater



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2. Aerobic groundwater (phreatic)
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5. Riverbank groundwater

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

1. Introduction

Public water supply requires large amounts of water which sources are normally limited to surface water and groundwater.

Groundwater can sometimes be abstracted at places near the distribution area, which makes transport pipes unnecessary. Furthermore, the water is hygienically reliable and typically has a constant composition. Sometimes, it can even be distributed without treatment, though a simple and cheap treatment is often inevitable. However, the amounts that can be abstracted are limited, and each abstraction results in a lowering of the groundwater table, which can harm agriculture and nature.

Because of the influence on the environment by desiccation, the national policy in the Netherlands aims at limiting groundwater abstraction and at switching, partially, to the use of surface water.

Groundwater can be classified in several types regarding its origin, the way it rises to the surface,

or the treatment that requires for drinking water production. This influences the treatment that will be required for production of drinking water.

Regarding its origin, the ground-water can be phreatic or artesian (Figure 1).

Phreatic groundwater is characterized by a free groundwater table, which is strongly influenced by the in- and outflow. Because of rainfall the groundwater table will rise, and outflow will lower the groundwater table. The groundwater level significantly fluctuates and the dynamic process is fully determined by hydrological and geohydrological conditions. Even without human interference, the natural groundwater table shows (large) variations.

Artesian water is groundwater that is located under a confining layer. This layer is responsible for the build-up of hydraulic pressure, which can cause water to come spontaneously to the surface, and for long aquifer residence times. Such residence times can either contribute for microbiological reliability or water quality deterioration (dissolving substances in anaerobic circumstances).

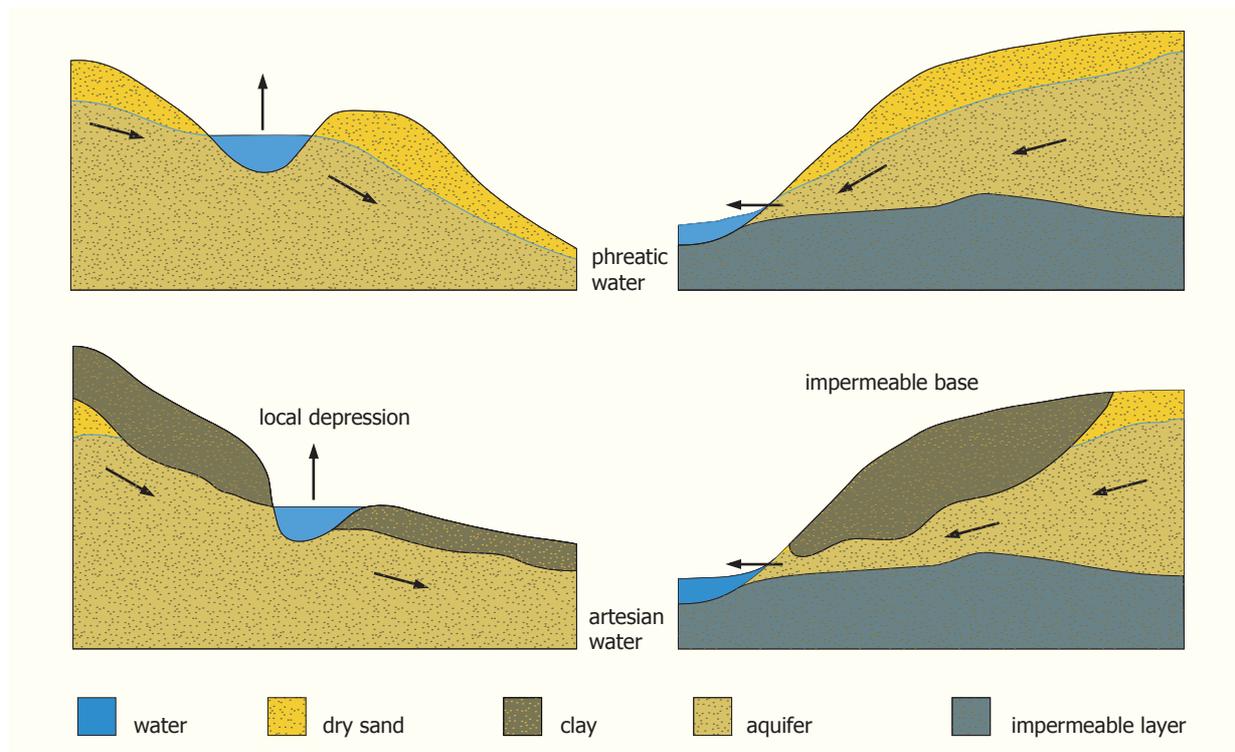


Figure 1 - Subdivision of springs

Regarding the rise of groundwater to the surface, this can be due to a local depression or to an impermeable base (Figure 1). Local depressions are common in nature. Examples of local depressions are brooks and streams which have an inflow that, even if significant, is often invisible. The rise of groundwater to the surface due to an impermeable base results in springs which can have up to high capacities.

Opposite flows occur with infiltrating rivers where water flows from the river into the groundwater. In the Netherlands this is common along the large rivers running beside polder areas. In this case, river water feeds the aquifers under upper clay and peat layers. This infiltrating water is discharged through ditches and drain facilities of the nearby polders and are often pumped off into the same river again.

Groundwater has a near-constant quality. Per location, however, large differences in water composition can be found. This composition depends on the natural environment from which the groundwater is abstracted, and the route that the water has followed to get there.

Four types of groundwater can roughly be distinguished with respect to the treatment in drinking water production:

- aerobic groundwater (phreatic)
- anoxic groundwater
- anaerobic groundwater
- riverbank groundwater

The above list implies that, for the treatment of groundwater, the level of oxygen (aerobic, anoxic or 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 four types of groundwater will be further discussed separately for both, their typical characteristics and their typical treatment schemes.

2. Aerobic groundwater (phreatic)

Phreatic groundwater has an open groundwater table and is, therefore, connected to the atmosphere. When the organic matter content of the soil is limited, the water does not lose its oxygen (i.e., does not 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. However, some treatment is usually necessary or desired. In aerobic phreatic groundwater, the parameters pH, Ca, SI (saturation index) and HCO_3^- are usually the ones that have to be taken into account. The other parameters generally comply with the legal requirements for water supply .

Aggressive (soft) 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 then smaller than 0. To make distribution of this water possible, the saturation index has to be increased.

In order to remove the aggressive CO_2 that can react with limestone and materials like concrete , it is necessary to neutralize the water, which always results in increase of pH (thus becoming less acid).

Neutralization can be achieved by the following methods:

- aeration/gas transfer
- limestone filtration
- dosing of a base

The method chosen is, to an important extent, determined by the desired water quality. Aggressive CO_2 is not permitted in drinking water, and the water needs to contain 1 mmol/l HCO_3^- at a minimum, while a content of 2 mmol/l is desirable for

a sufficient buffering capacity. Furthermore, the pH should be as high as possible to limit the dissolving of lead and copper into the water from the pipe materials.

The SI is increased when CO₂ is removed, while the other concentrations remain equal. Neutralizing with aeration can thus be done if the HCO₃⁻ concentration is already high enough.

The choice for an aeration system depends on the desired removal of CO₂. By neutralizing with aeration the water is brought in contact with air. Water that is in equilibrium with air will contain approximately 1 mg/l CO₂. Because the carbon dioxide content in groundwater is often much higher than equilibrium, the CO₂ will be transferred from the water to the air.

If the hardness of the water is high, the oxidation might result in a concentration of CO₂ that is lower than in equilibrium.. This may lead to limestone deposits in the aeration system and in the post-filtration.

When limestone (marble) filtration is applied, the requirements for SI, pH and HCO₃⁻ buffering can be met. With limestone filtration, aggressive water flows through a filter bed filled with calcium carbonate (marble) grains. The filter bed functions the same way as a sand filter. However, in this case, the marble grains dissolve slowly. When the grains have become very small, they will be removed during backwashing.

The filter bed is regularly replenished with new grain material.

In the case of limestone filtration, aggressive CO₂ is removed with the following reaction:
$$\text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + 2 \text{HCO}_3^-$$

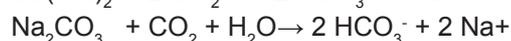
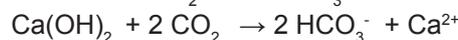
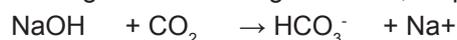
The hardness and mainly the bicarbonate content increase in limestone filtration. Limestone filtration is used for water with a low bicarbonate content and, therefore, a low buffering capacity. The concentrations at which the hardness and bicarbonate increase can be influenced by the choice of the

preliminary aeration method, influencing the CO₂ concentration.

The reaction mentioned above is an equilibrium reaction. This means that, on the one hand, the dosage of CaCO₃ added is never too much. On the other hand, the driving force decreases because of the reaction, and the reaction rate also decreases. The equilibrium is obtained after an infinitely long contact time. In practice, only a limited contact time is used. A bed height of 1.5 - 2 m with a filtration rate of 5 m/h is common. With a porosity of 0.35, a contact time of $(0.35 \cdot 1.75 / 5 =)$ 0.15 hour is realized and usually an SI of -0.3 is achieved. Larger bed heights are needed if aiming at the removal of iron, manganese and ammonium simultaneously. The increase in pH has a positive influence on oxidation rates.

Dosing of a base is done in practice with sodium hydroxide (NaOH), lime (Ca(OH)₂) or soda (Na₂CO₃).

leading to the following reactions, respectively:



When dosing a base, carbon dioxide is transformed into bicarbonate. The dosed concentration has to match exactly the concentration of CO₂ that has to be transformed. In the case of an underdose, the water remains acid, and in case of an overdose, over-saturation occurs resulting in the precipitation of CaCO₃. The dosage of a base for neutralization is only used when a small pH increase is desired. The two previously mentioned methods (aeration/gas transfer or limestone filtration) are simpler in operation and cheaper. Thus, dosing a base is only applied as a final correction of the pH.

Example of aggressive aerobic groundwater

An example of the aggressive aerobic groundwater treatment is the one of Hoenderloo pumping station (Netherlands), which consists of aeration/gas transfer followed by limestone filtration. Table 1 shows the annual averages of different parameters for raw water and clean water.

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 CO₂) and filtered through a limestone filter (decrease of the CO₂ concentration, increase of the HCO₃⁻ and the Ca²⁺ concentrations). The SI increases under the influence of the lower concentration of CO₂, and the higher concentrations of HCO₃⁻, and Ca²⁺; the water becomes less aggressive with respect to calcium carbonate.

Because of the use of limestone filtration, the HCO₃⁻ and the Ca²⁺ concentrations increase. More ions will get into the water, as a result of which the conductivity (EC) increases.

The increase in the HCO₃⁻ concentration can be calculated when it is assumed that all produced HCO₃⁻ comes from the limestone. For every formed mmol/l Ca²⁺, 2 mmol/l HCO₃⁻ are produced. At this pumping station the Ca²⁺ concentration increases 0.3475 mmol/l because of the limestone filtration, and the concentration of HCO₃⁻ has to be increased by $2 \cdot 0.3475 = 0.695$ mmol/l. There was 0.34 mmol/l HCO₃⁻ present in the raw water and thus,

there has to be $0.695 + 0.34 = 1.035$ mmol/l HCO₃⁻ in the treated water. This corresponds to 63.1 mg/l.

Hard water

Aerobic groundwater, which is abstracted from soils rich in calcium, is often very hard (>3 mmol/l). Due to the biological processes in the soil, the concentration of CO₂ can result in substantial dissolution of limestone, forming Ca²⁺ and HCO₃⁻ in the water.

Groundwater is sometimes in equilibrium regarding calcium carbonate (limestone). Water that is supersaturated with respect to calcium carbonate cannot be found in nature; a possible supersaturation would already have disappeared due to precipitation, given the long residence time.

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. The water becomes supersaturated with respect to calcium carbonate (SI > 0) due to the carbon dioxide removal.

To prevent limestone precipitation in the 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. The hardness (Ca²⁺ + Mg²⁺) of drinking water, according to Dutch regulations, may not be more than 2.5 mmol/l. Furthermore, it is desired that the pH is as high as possible to limit the lead and copper solvency. For a higher pH, a lower hardness is required. However, softening is not allowed lower than 1 mmol/l.

In the Netherlands, softening for the production of drinking water is most of the times executed with pellet reactors. In these reactors calcium is removed by dosing a base (caustic soda or lime) which leads to the formation of CaCO₃ pellets, that are reusable as chicken feed (for producing eggshells), or for neutralization purposes.

The softening occurs by dosing chemicals (NaOH or $\text{Ca}(\text{OH})_2$) into the water in cylindrical reactors with upward flow (Figure 2). 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. Alternatively, additional acid neutralization can be applied.

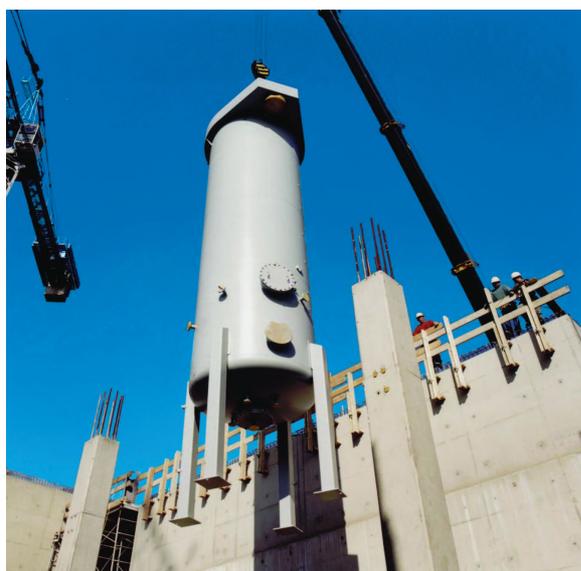


Figure 2 - Pellet reactor for softening water in Meerssen (Limburg)

3. Anoxic groundwater

Anoxic groundwater is found when the groundwater is located under a confining layer, and is characterized by the lack of oxygen and the presence of iron and manganese (and some ammonia).

The treatment of anoxic groundwater often consists of aeration followed by submerged granular media filtration (Figures 3 and 4).

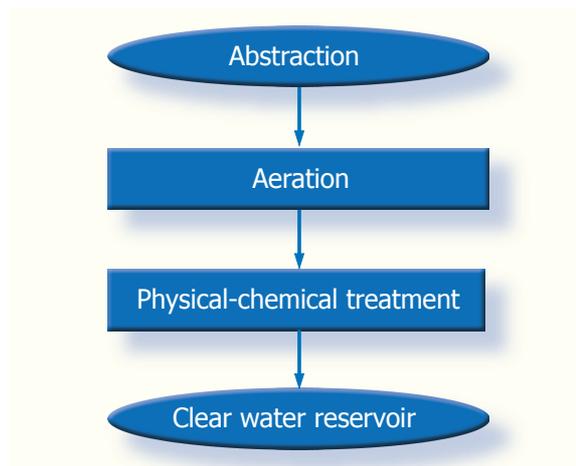


Figure 3 - Treatment of slightly anaerobic groundwater

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 in the filter bed.

The contact between air and water which is necessary for aeration can be obtained with various systems: by dropping the water through the air in fine droplets (spraying), by dividing the water into thin layers (tower aerators, cascades), or by blowing small bubbles of air through the water (deep well aerators, plate aerators, compressor aerators). The choice of a certain system is, to a great extent, determined by the gases that have to be removed or added. Table 2 gives a global indication of the effects of the various aeration systems.



Figure 4 - Aeration and submerged granular media filtration at the Noord-Bergum pumping station (Friesland)

Table 2 - Choice for a specific aeration system

Favorable effect	Potential system
Input of O ₂	All systems
Low removal of CO ₂	Compressor aeration, deep well aeration, cascades
Moderate removal of CO ₂	Spraying
High removal of CO ₂	Tower aeration
High removal of CH ₄	High cascades, plate aeration, tower aeration
High removal of H ₂ S	All systems, except compressor aeration
Removal of micropollutants	Tower aeration

Aeration is followed by submerged sand filtration. In groundwater filters, various chemical and biological processes take place, which all relate to the oxidation of dissolved groundwater components. Table 3 shows an overview of these processes. Filters consist of a (sand) bed of 1 - 2 m through which water flows. The filter is backwashed almost daily, through an upward water flow, which is most of the times complemented with an extra backwash air.

During filtration the oxidized ferric iron reacts with OH⁻ ions and is transformed into Fe(OH)₃ flocs, which are retained in the sand bed (a physical process). Manganese undergoes a partly chemical and partly biological transformation.

Iron (Fe²⁺)

In the oxidation and hydrolysis of iron, first the ferrous iron is oxidized, after which hydrolysis takes place and iron hydroxide flocs are formed. These flocs are filtered in the sand bed:

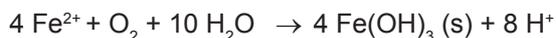
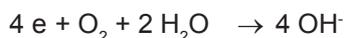


Table 3 - Processes used for groundwater filtration (in order of performance)

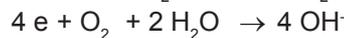
Process	Dominant mechanism
Oxidation and hydrolysis of Fe ³⁺	Chemical
Oxidation of CH ₄	Biologic
Oxidation of H ₂ S	Biologic
Oxidation of NH ₄ ⁺	Biologic
Oxidation of Mn ²⁺	Chemical (catalytic)

The rate at which oxidation and the hydrolysis of iron takes place depends on the pH. With a low pH the process develops slower than with a high pH. For that reason, when treating groundwater with a low pH, an aeration method is applied in which much of the CO₂ is removed and, therefore, a higher pH is achieved.

During the oxidation and hydrolysis of iron, acid is formed, so the process slows down itself, depending on the alkalinity of the water.

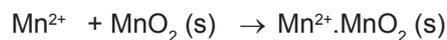
Manganese (Mn²⁺)

Mn²⁺ is oxidized in a sand filter to Mn⁴⁺:



The speed of this transformation is very slow, unless a certain amount of MnO₂ has already been deposited, working as a catalyzing agent for the further transformation.

The formed MnO₂ adsorbs free Mn²⁺:



The adsorption reaction is much faster than following oxidation with oxygen to MnO₂. With this adsorption, also the oxygen consumption for the removal of manganese is lower than would be expected based on a complete oxidation. In practice 30 - 90% of the manganese will be oxidized.

Manganese is deposited in the lower part of the filter, which can be observed by a black color. The deposits of manganese are hard to wash out, because they stick steadfastly to the sand grains, much more so than the flaky iron deposits. If the filter bed is too low (or the filter load too high), then manganese can even deposit on the filter nozzles. Because of the manganese deposits, the filter material has to be replaced regularly (sometimes annually), or externally cleaned.

Backwash water

As a result of removal of the iron hydroxide flocs and manganese oxides, the pore volume between the sand grains decreases. The result of this is the increase of the hydraulic resistance of the water when flowing through the filter bed. When this resistance becomes too large, the filter should be backwashed.

The backwash water production is usually 2 - 4% of the total drinking water production. Due to the scarcity of groundwater, such a production loss is undesirable. Furthermore, the backwash water can't be discharged, without treatment on surface water.

Backwash is sent to a buffer reservoir, which is followed by a treatment installation.

The most suitable treatment processes for backwash water is titled plate sedimentation, in case the treated water is discharged on surface water; and ultrafiltration (Figure 5), in case the treated water is used for production of drinking water.

In ultrafiltration, the water is put under pressure and forced to flow through a tubular, or capillary, membrane, which remove all suspended contaminants.. Each 10 - 20 minutes the membrane has to



Figure 5 - Backwash water treatment with tubular membranes (Air-flush®) at Spannenburg pumping station (Friesland)

be backwashed and the concentrated backwash water is released.

The settled sludge or concentrated backwash water can be thickened further in a storage and thickening buffer. The thickened sludge can be reused as an additive for the production of bricks or as phosphate binder (after acidification) in wastewater treatment.

If the thickened sludge can't be reused, it is sent to a dump site. In a few cases the backwash water sludge has a high content of arsenic, making it a chemical waste.

Example of the treatment of anoxic groundwater
An example of anoxic groundwater treatment is the one of the pumping station of Zutphenseweg, in the Netherlands, which consists of aeration/gas transfer followed by sand filtration and a second aeration. Table 4 shows the averaged values of the different parameters over a year. As a result of aeration the concentration of CO₂ decreases and the pH of the water increases. Due to aeration the concentration of oxygen increases to a value near

Table 4 - 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	-	-

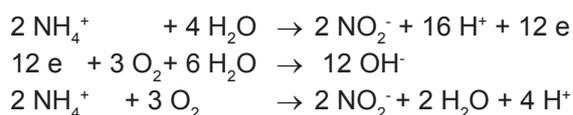
the saturation value (ca. 10 mg/l). The concentrations of Fe²⁺, Mn²⁺ (and NH₄⁺) decrease due to the oxidation and biological transformations. The oxygen consumption is approximately 2.8 mg/l. To get a higher oxygen content in the produced water, post-aeration is used.

4. Anaerobic groundwater

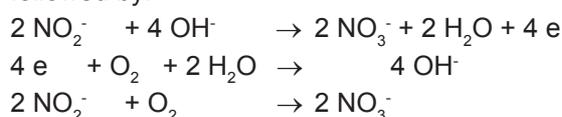
Anaerobic groundwater is found when the water is abstracted under a confining layer and no oxygen is present in the water. Furthermore, there is also no nitrate present and organic material is broken down with sulfate as an oxidant. Iron, manganese and especially ammonium are present in high concentrations, while hydrogen sulfide and methane are also present in the groundwater. Abstracted anaerobic groundwater might contain iron in concentrations of several milligrams per liter and, in exceptional cases, up to 25 mg/l; manganese in concentrations of less than 1 mg/l and, in exceptional cases, up to 2 mg/l; and ammonium in concentrations up to several milligrams per liter and, in exceptional cases, up to 10 mg/l.

For the treatment of groundwater, aeration aims to increase the oxygen content and to decrease the concentrations of carbon dioxide, methane, hydrogen sulfide (as well as other volatile organic compounds), and iron, manganese and ammonium. Therefore, several aeration and filtration steps are needed for the production of drinking water.

During the filtration step, NH₄⁺ is at first oxidized to nitrite and subsequently oxidized to nitrate by so-called ammonium oxidising bacteria:



followed by:



in total:



The biological transformations take place simultaneously and it can take several weeks after start-up of a new filter before they are complete, the so-called ripening period. For the removal of ammonium good management of the biomass is of great importance. If the backwash is made too often, the amount of biomass can become too small but if the backwash is not made enough times the accumulation of biomass can occur. This accumulation results in the growth of other bacteria, like *Aeromonas*, and even in the formation of anaerobic zones in the biomass itself.

During the removal of ammonium, a lot of oxygen, 3.55 mg/L, are consumed and 3.44 mg/L nitrate are produced

When the ammonium content is larger than 3 mg/l, the concentration of oxygen necessary for the removal of the ammonium is larger than the total concentration of oxygen, which can be dissolved in water (i.e, the saturation concentration).

In submerged filters the available concentration of oxygen is limited to approximately 9 - 12 mg/l (depending on the water temperature). If the process needs more oxygen, then dry (or trickling) filtration should be used. In this case, oxygen is added continuously during filtration making the water to be almost always saturated.

In order to remove the particles that might breakthrough during trickling filtration, submerged filtration is used after the trickling filters.

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 6 and 7). A trickling filter does not have a layer of water, like in submerged filtration. In the dry filter the water flows down past the grains, with a size of 0.8-4 mm in diameter, at the same time that air is flowing. The oxygen in the air replenishes the oxygen in the water, which is used by the bacteria. In this way more than 3 mg/l

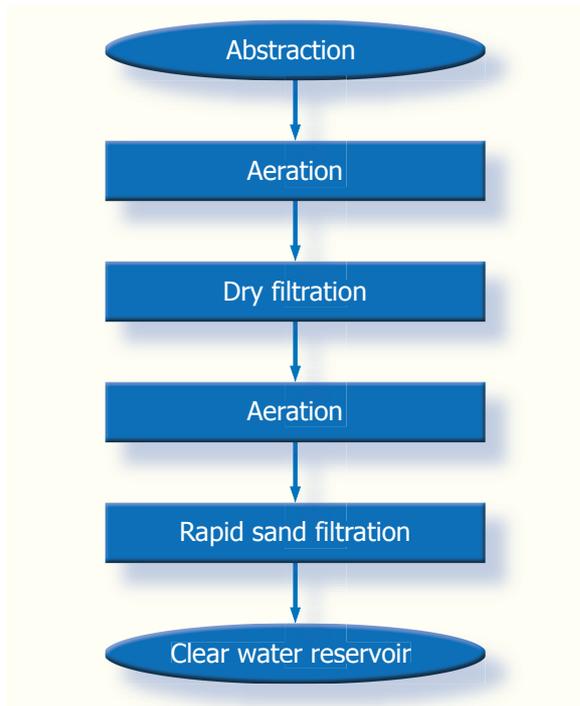


Figure 6 - Treatment of deep anaerobic groundwater

of ammonium can be transformed without anaerobic results in the filter.

Example

An example of anaerobic groundwater treatment, is the one of the St. Jansklooster pumping station, in the Netherlands, which consists of aeration, trickling filtration, aeration and submerged filtration. Table 5 shows the averaged values over a year for the different parameters.

As a result of the aeration phases, the concentration of carbon dioxide decreases and the pH increases. Furthermore, the concentration of oxygen increases. The concentrations of Fe^{2+} , Mn^{2+}

Table 5 - 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	-	-

and NH_4^+ decrease because of chemical and biological transformations; the concentration of nitrate, on the other hand, increases. The concentration of nitrate increases less than the theoretical calculation.

5. Riverbank groundwater

Riverbank groundwater is groundwater that is abstracted directly adjacent to surface water, usually a river. Such groundwater is a mixture between

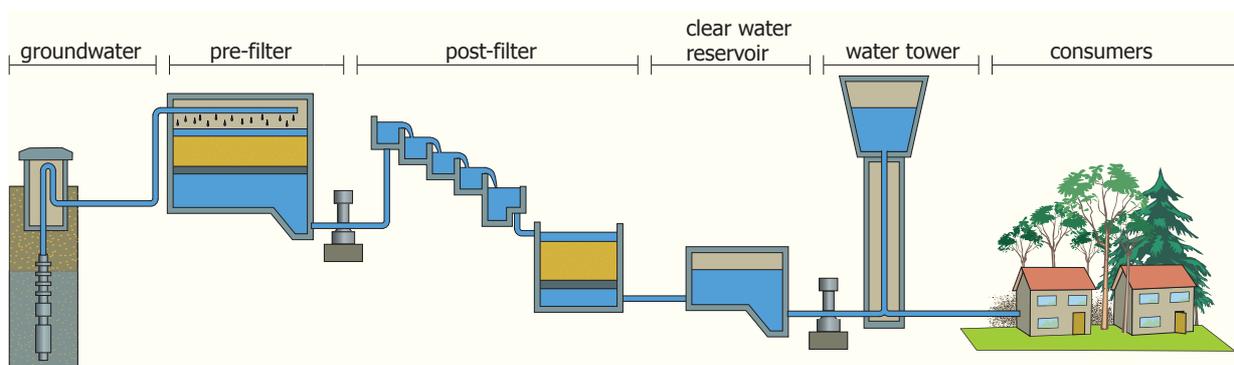


Figure 7 - Treatment of groundwater with double aeration/filtration

aerobic “ex-surface water” infiltrated into the soil via the riverbank with natural anaerobic or anoxic “old” groundwater.

This water is normally abstracted between 200 and 1000 m from the river. When the water is passing through the soil, all (harmful) bacteria are removed, producing a good microbiological water quality. Due to the long residence time in the soil, the treatment of riverbank groundwater has many similarities to the treatment of anoxic or anaerobic groundwater.

The treatment scheme for riverbank groundwater is shown in Figure 8. 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

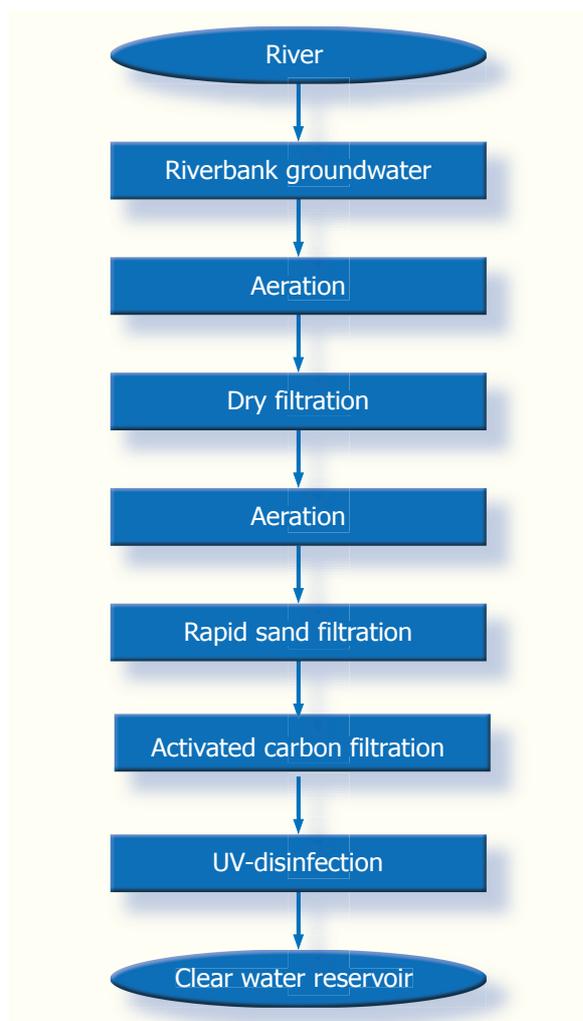


Figure 8 - Treatment of riverbank groundwater

concentrations of ammonium, which are biologically transformed to nitrate, a lack of oxygen can occur in the treatment; therefore, an extra trickling filtration stage is often included (Figure 9).

Activated carbon filtration is also used for the treatment of riverbank groundwater because of taste problems and due to the presence of organic



Figure 9 - Aeration over a dry filter in Zwijndrecht (Zuid-Holland)

micropollutants (such as herbicides and pesticides) infiltrating from the river.

UV is often applied as the last disinfection stage. In the activated carbon filters there might be grow of microorganisms due to the breakdown of organic material, which end up in the filtrate. With UV-disinfection the microorganisms are killed, without the formation of disinfection by-products.

Compared to surface water, riverbank groundwater has the advantage of microbiological reliability and a much more stable and predictable quality. This means that no large reservoirs and infiltration facilities are needed and less sludge is produced. Riverbank groundwater is thus a reliable source of drinking water supply, which in some respect can be seen as a golden compromise between groundwater and surface water.

Research has shown that residence times shorter than 60 days can be good enough to guarantee hygienic reliability and an optimal design of the well (including a location perpendicular to the river) can

lead to a very good quality levelling. This makes it possible to retrieve good water quality with minimum effects on the environment. In such cases, the riverbank groundwater is called riverbank filtrate. The treatment of riverbank filtrate doesn't show many differences from the treatment of riverbank groundwater. Only that in this case, the share of surface water is larger, which makes activated carbon filtration and post-UV-disinfection even more important.

Activated carbon filtration

Activated carbon filtration is a treatment process based on adsorption. During this process substances adhere to the surface through surface and Van de Waals forces. In drinking water production this process allows the adsorption of apolar micropollutants, such as most pesticides and herbicides like Bentazon and Atrazine. The water flows downwards through a filter bed of activated carbon grains.

An important process parameter during activated carbon filtration is the time in which the equilibrium has to be reached. For practical purposes, empty bed contact time (EBCT) is used. Often an EBCT between 12 and 40 minutes is used. The true contact time is, of course, shorter depending on the porosity of the grain bed.

The amount of water that can be treated in the filter before breakthrough occurs, is expressed as the number of bed volumes. In practice, lifetimes of 10,000 to 30,000 bed volumes are possible, depending on the contaminants that have to be removed. At a bed height, for example, of 3 m and 10,000 bed volumes, the total amount of treated water is $(3 \cdot 10,000 =) 30,000$ m. At a (superficial) filtration rate of 5 m/h, this corresponds to a lifetime of $(30,000/5 =) 6,000$ hour, or almost 0.7 year.

Next to the micro-contaminants, which have to be removed, natural organic matter (NOM) also sticks to the surface, which competes to the micropollutants

Activated carbon filtration shows great similarity to the previously mentioned rapid sand filtration process. Structurally, all the external characteristics are the same (dimensions, bed height, floor construction, measurement tools, etc.). For activated carbon filtration, the filter bed does not consist of sand but of activated carbon grains, with a diameter between 0.5 and 1.5 mm and a density between 300 - 500 kg/m³.

Activated carbon is made by heating organic carbon (wood, peat, coal, coconut), resulting in a very porous material with a very high specific surface (500 - 1,500 m²/g). The pores have very diverse dimensions (0.1 - 1,000 nm). The smallest pores are the most important ones for the surface effects, while the larger pores serve as a transport channel to the smaller pores (Figure 10).

Contaminated carbon can be regenerated. In this process the carbon is heated again. The adsorbed contaminants are burned or volatilized during this process. At such regeneration, 5 - 10 % of the carbon is lost.

Example of the treatment of riverbank groundwater
An example of riverbank groundwater treatment, is the one at the Nieuw-Lekkerland pumping station, in The Netherlands. Table 6 shows that the

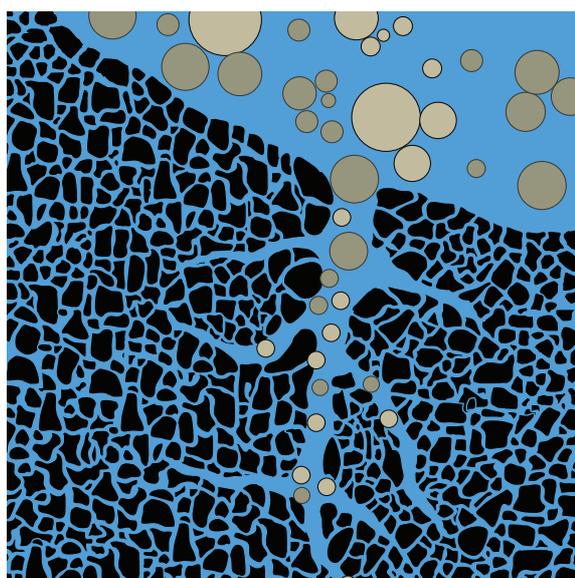


Figure 10 - Micropores and pore channels in an activated carbon grain

Table 6 - 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	-	-

water contains a high concentration of ammonium and that there are pesticides present in the water. Hence, the treatment scheme consists of: aeration, trickling filtration, aeration, submerged filtration, activated carbon filtration, and (low pressure) UV-disinfection.

The oxygen concentration increases because of the aeration steps, while the manganese and iron concentrations decrease because of the combination of aeration and filtration. The ammonium concentration decreases because of transformation in the trickling and submerged filters, leading to the increase of the nitrate concentration. Because of activated carbon filtration, the Bentazon concentration decreases.

There are no E-coli in the raw water because of the long residence times in the sub-soil. However, during UV-disinfection, possible (opportunistic) micro-organisms that grow in the activated carbon filter are eliminated.