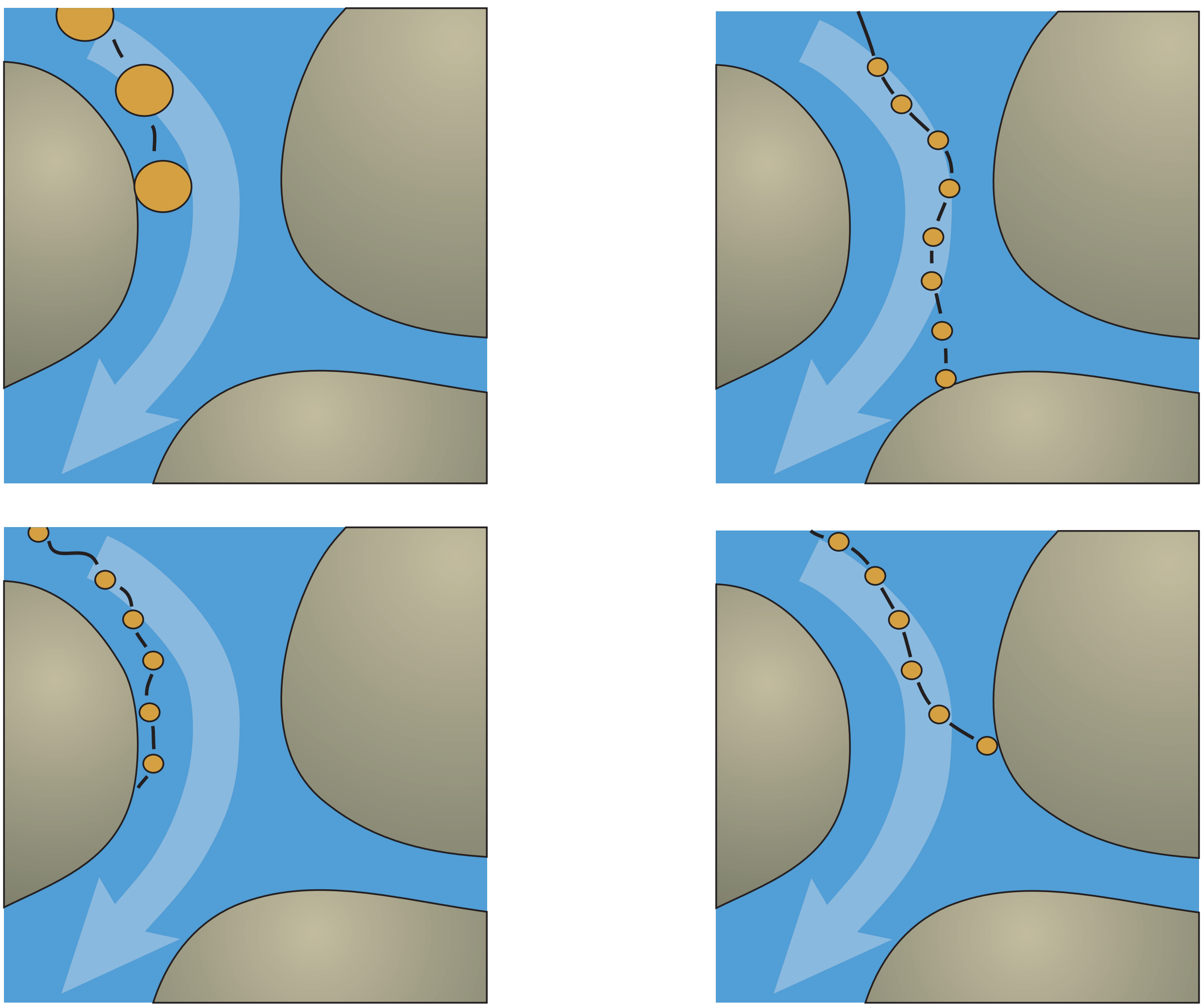
Granular filtration



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

1. Introduction

Filtration is a process where water flows through a permeable layer, either a membrane, filter paper, a sieve or a porous medium.
In water treatment, granular filtration is a process where water flows through granular material (often sand) while suspended solids (sand, clay, iron and aluminum flocs) are retained, some substances are biochemically decomposed and pathogenic microorganisms (bacteria, viruses, protozoa) are removed.

Biochemical reactions during filtration are especially important for groundwater treatment, which requires the oxidation of iron, manganese, ammonium and, in case of poor gas stripping, methane..
The removal of pathogenic microorganisms, which occurs by decay and retention on the (sand) grains, is important for surface water treatment, and it has an efficiency of 90 to 99%.

The most common application of filtration is rapid sand filtration (Figure 1), i.e, filtration operated at high rates (5 to 20 m/h), which is present in nearly every water treatment plant

In surface water treatment, the filters are placed after floc formation to get rid of the remaining flocs and pathogens and to decompose ammonium.
In groundwater treatment, the filters are usually placed after aeration to remove iron flocs, manganese and ammonium. With softening, filters are often placed after pellet reactors to remove the 'carry-over'.

2. Filtration mechanisms

When water flows through the filter bed, suspended and colloidal particles are retained by the filter material.

Particles that are larger than the pores in the filter bed will remain on the bed.

If smaller filter material is used, the pores are also smaller and the screening process results in the so-called cake filtration. The cake will retain small particles, and treatment occurs mainly in the top layer of the filter.
The disadvantage of cake filtration is that with high concentrations of suspended and colloidal particles, rapid clogging of the filter bed occurs.

During rapid sand filtration the removal of suspended and colloidal particles usually occurs inside the filter bed (Figure 2).
Thus, the clogging is spread over the entire height of the filter bed.
The suspended and colloidal particles are transported to the filter material in different ways (Figure 3).
Generally, the particle follows the trajectory of the water that flows through the filter bed. This trajectory follows the complicated pore structure of the bed. When the trajectory curves, a heavy particle can be transported to the filter material due to inertia. If the trajectory approaches the filter grains, then particles can also be intercepted. Heavy particles are especially subject to sedimentation, lighter particles to diffusion. By the turbulence of the water, particles can reach spaces between the grains. Due to these mechanisms, the particle

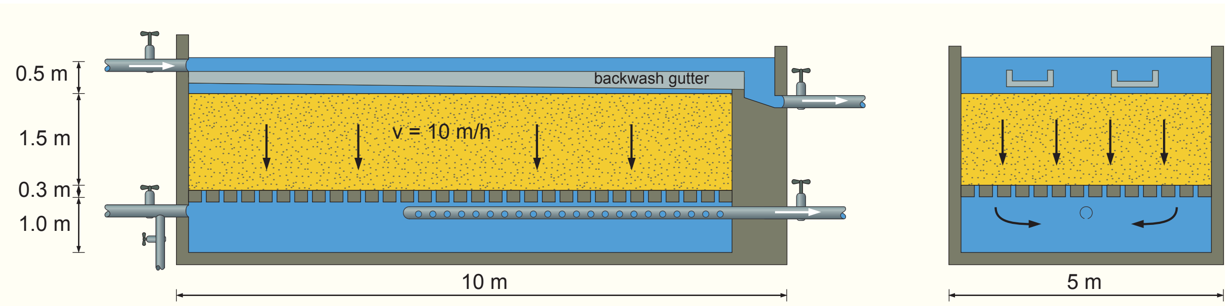

Figure 1 - Principle of rapid sand filtration(side and front view respectively)

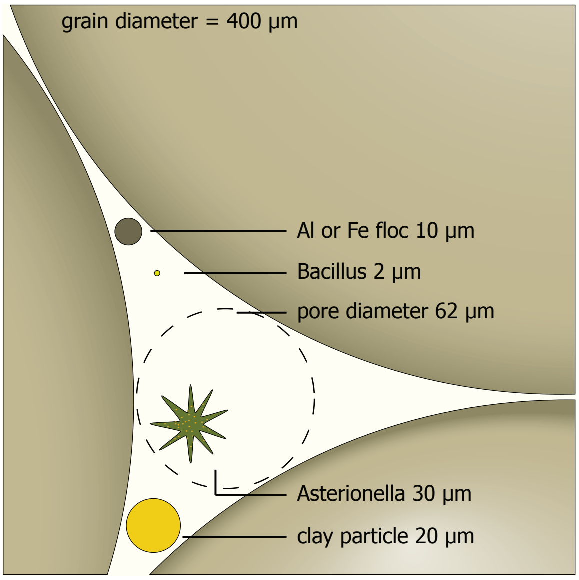

Figure 2 - Principle of screening

can switch to other trajectories that flow nearer to a grain or can collide directly with a grain, and it remains at the surface of the grain.

When the suspended and colloidal particles collide with the filter grains, attachment could take place. There are two types of forces that result in attraction and repulsion of the particles.
The VanderWaals forces ensure that two bodies are attracted.
Electrostatic forces can have an attracting or repulsing effect, depending on the charge of the particles.
In general the filter material (sand) and the suspended and colloidal particles have a negative charge and repulsion takes place.

In addition to physical processes to remove suspended and colloidal solids as described above, chemical and biological processes occur in the filter bed.
Iron(II) and manganese are removed by oxidation from groundwater. By adding oxygen in the preceding aeration step, iron(II) will be transformed into iron(III) and iron flocs will be formed. The iron flocs are removed by the same mechanisms as described for the removal of suspended and colloidal particles.

Manganese is transformed to manganese oxide in the presence of previously deposited manganese oxide (catalytic process).
Consequently, it can take several months before manganese removal starts. Therefore, it is necessary to avoid the total removal of manganese oxide during backwashing in order to keep the oxidation process alive.
Literature suggests that manganese is also oxidized by biological process.
Other biological processes in the filter bed are the decomposition of methane, ammonium, and (biodegradable) organic matter.
The decomposition of methane in the filter bed has to be avoided, because it results in an uninhibited growth of bacteria, which can lead to clogging and breakthrough. Methane, therefore, must be removed early in the process.

Ammonium is transformed into nitrate in two steps. A group of nitrifiers (nitrosomonas) transforms ammonium into nitrite whereas another group of nitrifiers (nitrobacteria) transform nitrite into nitrate.
The nitrifiers are situated on the surface of the filter material and for growth they use energy that is produced during the transformation of ammonium or nitrite. The amount of ammonium that can be transformed depends on the growth rate of the bacteria, the size of the bacteria population, and the amount of ammonium that is transported to the bacteria (by diffusion).
In the beginning the growth rate of the bacteria is optimal and uninhibited. The population dur-

Chemical and biological decompositions in the filter bed

$$4\ Fe^{2+} + O_2 + 2\ H_20 + 8\ HCO_3^- \rightarrow 4\ Fe(OH)_3 + 8\ CO_2$$
$$2\ Mn^{2+} + O_2 + 6\ H_2O \rightarrow 2\ MnO_2 + 4\ H_3O^+$$
$$NH_4^+ + 2\ O_2 + 2\ H_3O^+ \rightarrow NO_3^- + 3\ H_2O$$

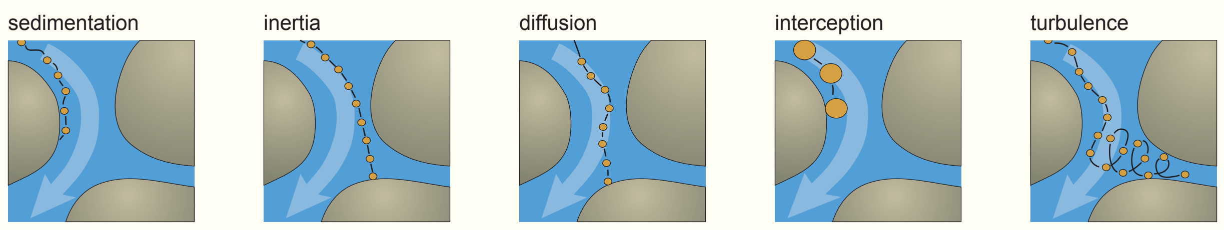

Figure 3 - Transport of impurities towards the grain

ing this lag phase is small and little ammonium is transformed. After some time the population grows and finally stabilizes (when growth is equal to decay). At that time the maximum ammonium removal occurs.

For the chemical removal of iron and manganese,,the oxygen consumption is limited.
Iron is normally present in concentrations lower than 10 mg/l and manganese concentrations are seldom above 1 mg/l. The oxygen concentrations that are needed for these reactions are obtained after aeration, (approximately 10 mg/l).
For the biological removal of ammonium and/or methane, the oxygen consumption is considerably higher than in the chemical removal of iron and manganese. When low concentrations of ammonium and/or methane are present in the water (few mg/l), the amount of oxygen that can be dissolved in water under atmospheric conditions is insufficient to complete these reactions.

3. Column tests

To determine the dimensions of a filter, the experience of other treatment plants that deal with similar water should be considered.
In addition, column tests (Figure 4) should be performed to find the optimal combination of the following parameters:
- grain diameter of filter material
- filtration velocity
- height of the filter bed
- height of the supernatant water.

The optimal combination leads to a filter that , satisfies the required effluent quality and it has a reasonable filter run time. In addition, the suspended solids should be divided over the filter bed height to avoid cake filtration.

The filter surface area has to be as small as possible to reduce investment costs.
Consequently, the filtration velocity has to be high. The higher the filtration velocity, the sooner the effluent quality will deteriorate during the filter run. This can be compensated for by increasing the filter bed height or by choosing filter material with a smaller grain size.
A higher filter bed, however, requires a higher filter construction and it is, therefore, more expensive..
Filter material with a smaller grain size clogs faster, leading to shorter filter runs which increase the operational costs.
In the graphs of Figure 5 the effluent quality and the filter resistance are represented for different filter materials and for different filter bed heights.

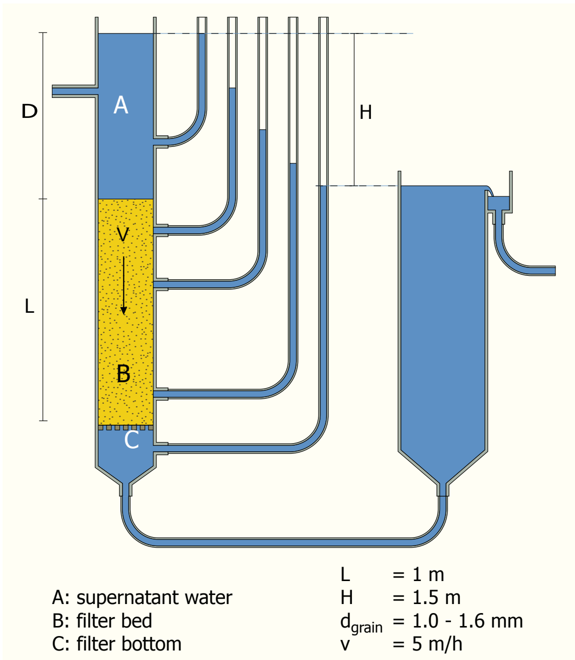

Figure 4 - Filtration, experimental setup

In general it is assumed that the effluent quality has to remain under a determined guideline value. The filter run time during which the effluent quality satisfies the guideline is called Tq.
Normally, filters are backwashed after run time Tr, when a predetermined maximum resistance is reached.
To prevent that the water quality deteriorates before the maximum resistance is reached, the filter design should fulfill the condition: Tr<Tq.
The aforementioned design parameters determine the values of both Tq and Tr (Figure 5).
In practice, there are some restrictions in the optimization process.
Normally, safety margins are introduced to maintain the quality of drinking water above all suspicion and filter run times of 1 to 2 days are used.
In addition, future extention should be always taken into account. Consequently, most of the time a filter is operated below its capacity and far from the optimal situation.

4. Theory

4.1 Filtration

Without using filtration theory, a long series of filtration experiments would be necessary to find an optimal solution for an installation.
Since the raw water quality varies during the year, experiments would take at least a year to be completed.
However, using the filtration theory,to predict the effects of changes in parameters, reduces the number of filtration experiments for an optimal design

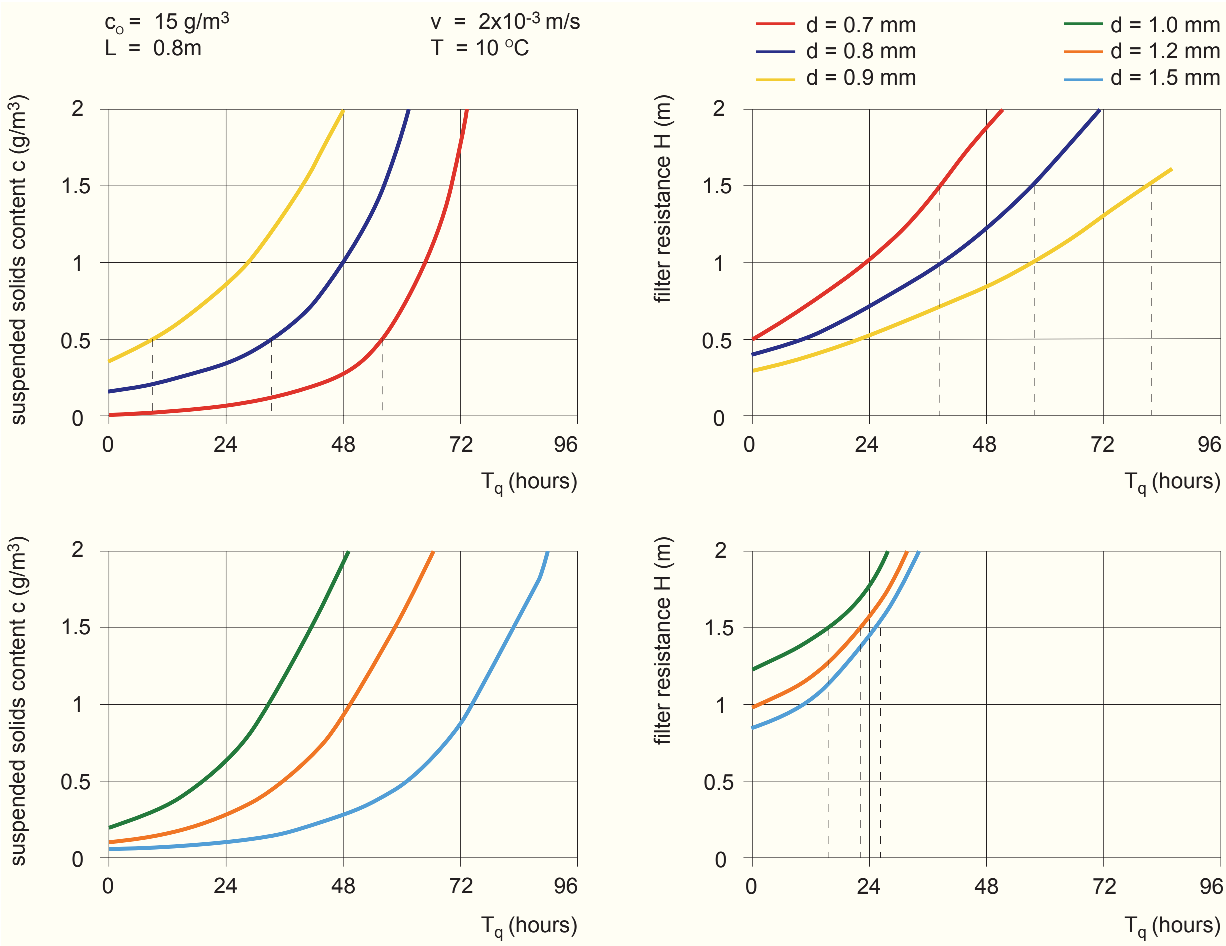

Figure 5 - Results of different filter runs to obtain an optimally functioning filter

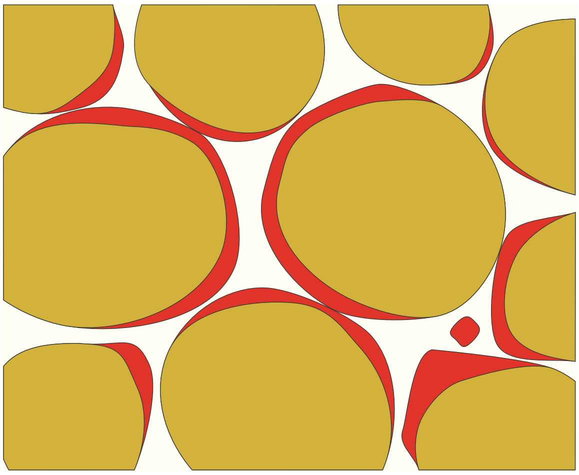

Figure 6 - Reduction of pore volume as a result of accumulated solids

Effluent quality

During the filtration process suspended and colloidal solids accumulate on the grains (Figure 6). Consequently, the concentration of suspended and colloidal solids in the water decreases with the increasing filter bed depth.
In addition, the pore volume is reduced in time due to the accumulation of suspended and colloidal solids, and the grain size of the filter material is increased.
With a constant filtration rate (superficial velocity), the water velocity in the pores increases as filter clogging proceeds.

The variation of concentration of suspended and colloidal solids is given by:

$$\frac{\partial c}{\partial t} = -u \cdot \frac{\partial c}{\partial y} - \lambda \cdot u \cdot c$$

together with the mass balance:

$$\frac{\partial \sigma}{\partial t} = -v \cdot \frac{\partial c}{\partial y}$$

in which:

c	=	concentration of suspended and colloidal solids	(g/m^3)
y	=	depth of the filter bed	(m)
v	=	filtration rate	(m/s)
p	=	porosity	(%)
u	=	pore velocity (=v/p)	(m/s)
λ	=	filtration coefficient	(m^{-1})
σ	=	accumulated solids	(g/m^3)

In the stationary situation (when the concentration is constant) the following is valid:

$$\frac{\partial c}{\partial t} = 0$$

therefore the kinetics equation is transformed into:

$$\frac{\partial c}{\partial y} = -\lambda \cdot c$$

To solve the system of equations the value of the filtration coefficient, λ must be known.
However, λ depends on different factors, such as the filtration velocity, viscosity, grain size, quality of the raw water, and the clogging of the bed.
After start-up of the filtration process, the filtration coefficient initially increases because of better attachment characteristics on the preloaded material.
Due to pore clogging, the pore velocity increases and fewer solids accumulate, expressed by a lower filtration coefficient λ.
When the solids are retained in the top layer of the filter bed, lower layers will take over until the filter is saturated and the filter breaks through.

The clean bed filtration coefficient λ_0 and the relationship between λ and σ have to be determined in practice, through column experiments.
Several researchers have found empirical relationships, such as those described by Lerk and Maroudas.

Lerk:

$$\lambda_0 = \frac{k_1}{v \cdot \nu \cdot d^3}$$

Maroudas:

$$\lambda = \lambda_0 \cdot \left(1 - k_2 \cdot \frac{\sigma}{\rho_d \cdot p_0}\right)$$

in which:
d = grain size (m)
p_0 = initial porosity (%)
k_1, k_2 = constants
ν = kinematic viscosity (m^2/s)

The ratio between the accumulated solids σ and the density is the reduction in pore volume (σ_v)

$$\frac{\sigma}{\rho_d} = \sigma_v$$

in which:
ρd = density of the flocs (kg/m^3)
σv = volume concentration in pores (m^3/m^3)

The value of the constant k_1 is often assumed to be $9 \cdot 10^{-18}$ and the constant k_2 is the reciprocal value of the maximum pore filling n (0<n<1).

Notice that in the case of Madouras it is assumed that the filtration coefficient decreases linearly as clogging increases. Although this is a simplification, with this assumption the system of equations can be solved.
With the boundary conditions y = 0, c = c_0 and the initial condition t = 0, σ_v = 0 and:

$$\alpha = \frac{v \cdot c_0 \cdot \lambda_0}{n \cdot \rho_d \cdot p_0}$$

The solution is, in general:

$$c = c_0 \cdot \frac{e^{\alpha \cdot t}}{e^{\lambda_0 \cdot t} + e^{\alpha \cdot t} - 1}$$

And, specifically for the effluent (y=L):

$$c_e = c_0 \cdot \frac{e^{\alpha \cdot t}}{e^{\lambda_0 \cdot t} + e^{\alpha \cdot t} - 1}$$

and:

$$\sigma_v = n \cdot p_0 \cdot \frac{e^{\alpha \cdot t} - 1}{e^{\lambda_0 \cdot y} + e^{\alpha \cdot t} - 1}$$

Filter resistance
During filtration, pore clogging increases resulting in the increase of the filter bed resistance.
When the filter reaches the maximum available head loss, a backwash is needed to avoid a decrease in the filtration velocity. The maximum available head loss is the difference between the supernatant water level and the head of the outflowing water, minus the clean bed resistance and head loss caused by filter bottoms, pipes and valves (Figure 7).

The clean bed resistance (H_0) can be derived from the equation of a flow through a pipe (pore) and is described with the Carman-Kozeney equation:

$$I_0 = \frac{H_0}{L} = 180 \cdot \frac{\nu}{g} \cdot \frac{(1-p_0)^2}{p_0^{\,3}} \cdot \frac{v}{d_0^{\,2}}$$

in which:
I_0 = initial resistance gradient (-)

This equation (the linear relationship between velocity and resistance) is only valid when:

$$Re = \frac{1}{p_0} \cdot \frac{v \cdot d_0}{\nu} < 5$$

When clogging occurs, the resistance formula changes to:

$$I = I_0 \cdot \left(\frac{p_0}{p_0 - \sigma_v} \right)^2$$

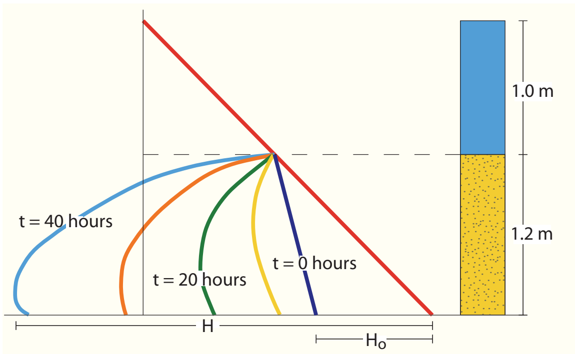

Figure 7 - Progress of the filter bed resistance in time, the so-called Lindquist diagram

in which:

I = resistance gradient(-)

The solids accumulation in the pores, σ_v, is known along the height and thus the resistance gradient can be calculated over the height of the filter bed. By integrating the gradient, the total resistance over the filter bed can be calculated.

As presented in Figure 7 the largest resistance is built up in the upper layers of the filter bed, where most of the solids accumulate.

In the lower layers the resistance gradient is almost equal to the clean bed gradient.

In time the resistance in the upper layers will increase.

A pressure drop in the filter bed below atmospheric (negative pressure) must be avoided. In such a case, dissolved gases come out of solution and, the filter bed is disturbed by the released gas bubbles.

Accumulated gas bubbles hinder downward water movement, which increases the filter resistance, ending filter runs prematurely.

Negative pressure can be avoided by maintaining a high supernatant water level and shortening filter runs. This can be achieved by increasing the height of the outflow weir.

4.2 Backwashing

After a certain period of filtration the pores in a filter bed are filled with accumulated suspended solids. Therefore, the porosity has decreased from p_0 to p, which results in a higher resistance and/or a poor effluent quality. At this moment, the filters are cleaned by backwashing with clean water (filtrate).

During backwashing, the water flows in an upward direction through the filter. The water scours the filter grains, erodes the accumulated solids from the filter material, expands the filter bed, and transports the solids towards the backwash troughs.

The larger the diameter of the grains, the larger the shear forces.

From practice, it is known that backwashing is difficult when the grains have a diameter smaller than 0.8 mm. Therefore, a combination of water and air is used (Figure 8). Air creates more turbulence which facilitates the removal of the solids from the pores.

Hydraulics of backwashing

Bed expansion (Figure 9) is an important parameter for the design of a backwash facility:

$$E = \frac{L_e - L_0}{L_0}$$

in which:

E	=	bed expansion	(-)
L_0	=	initial height of the filter bed	(m)
L_e	=	height of the expanded filter bed	(m)

The applied bed expansion depends on the diameter of the filter material.

When the filter material has a diameter of 0.8 mm an expansion of 15 to 20% is used, while a diameter of 1.2 mm requires an expansion of 10%.

During backwashing, there is no loss of filter material, if the filter is well designed. When the initial porosity (p_0), the height of the filter bed during filtration, and the height during backwashing are known, the porosity during expansion can be calculated:

$$(1-p_0)\cdot L_0 = (1-p_e)\cdot L_e \Rightarrow p_e = \frac{p_0 + E}{1+E}$$

in which:

pe = porosity of the expanded bed

A backwash rate of 40 m/h through a filter bed with a porosity of 40%, a grain diameter of 1 mm and a temperature of 10 °C gives a Reynolds number of 14.1. Thus, the water flow during backwashing is no longer laminar, but situated in the transition zone between laminar and turbulent, and the Karman-Kozeney equation is not valid.

From experiments, the resistance during backwashing can be described by the following equation:

Figure 8 - Filtration, backwashing with water and air

$$H = 130 \cdot \frac{\nu^{0.8}}{g} \cdot \frac{(1-p_e)^{1.8}}{p_e{}^{3}} \cdot \frac{v^{1.2}}{d^{1.8}} \cdot L_e$$

This empirical equation is valid until the upward flow rate becomes so high that the bed fluidizes: the grains do not support each other and float. Fluidization occurs when the resistance is equal to the mass of the filter bed under water:

$$\rho_w \cdot g \cdot H_{max} = (1-p) \cdot L \cdot (\rho_f - \rho_w) \cdot g$$

$$H_{max} = (1-p) \cdot L \cdot \left(\frac{\rho_f - \rho_w}{\rho_w} \right)$$

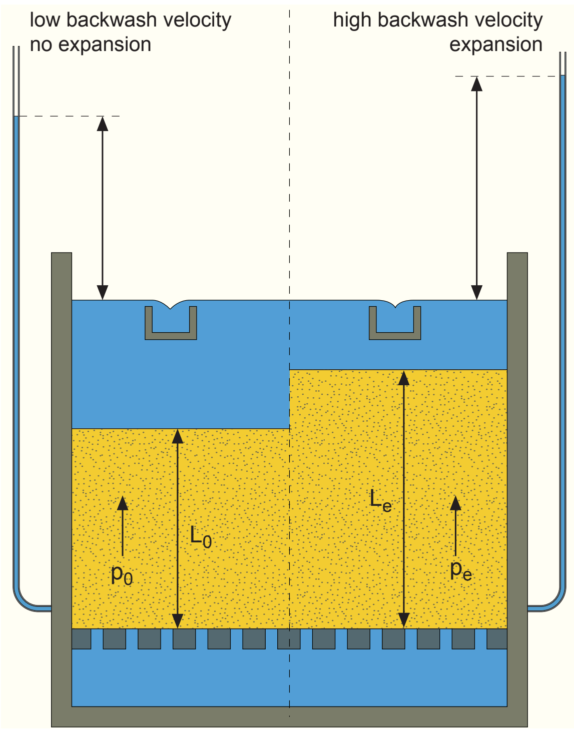

Figure 9 - A non-expanded and expanded filter bed

When sand is used as filter material (ρf = 2600 kg/m³ and p=0.4), the maximum resistance is almost equal to the bed height, since after substituting the values in the equation follows that H»L.

Figure 10 represents the resistance as a function of the backwash velocity. From the graphs it can be concluded that the maximum resistance is independent of the grain diameter.

The backwash velocity needed to achieve a certain expansion E and a resulting porosity pe, can be calculated with a combination of equations given earlier:

$$(1-p) \cdot L \cdot \left(\frac{\rho_f - \rho_w}{\rho_w} \right) = 130 \cdot \frac{\nu^{0.8}}{g} \cdot \frac{(1-p_e)^{1.8}}{p_e{}^{3}} \cdot \frac{v^{1.2}}{d^{1.8}} \cdot L$$

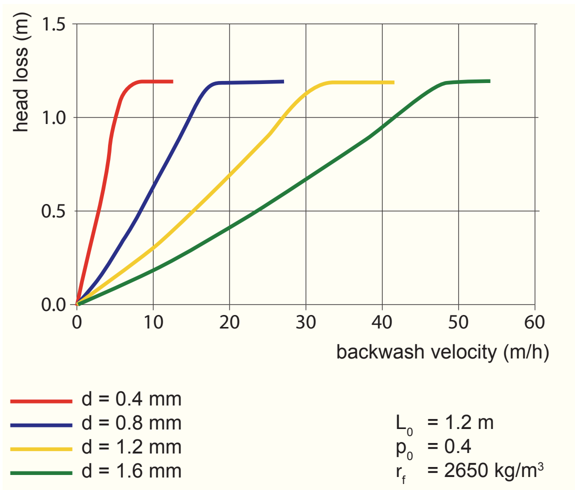

Figure 10 - Resistance during backwashing a sand filter bed with a height of 1.2 m as a function of the backwash velocity and grain diameter

From this equation it follows that:

$$v^{1.2} = \frac{g}{130 \cdot \nu^{0.8}} \cdot \left(\frac{\rho_f - \rho_w}{\rho_w}\right) \cdot \frac{p_e^{\ 3}}{(1-p_e)^{0.8}} \cdot d^{1.8}$$

Table 1 shows the backwash rate under variable bed expansions and water temperatures. To achieve a bed expansion of 20% a backwash rate of more than 30 m/h is necessary, which is considerably higher than the filtration rate from 1 to 20 m/h (for rapid filtration).

5 Practice

5.1 Construction

A rapid sand filter consists, most often, of an open tank of reinforced concrete.
The height of this tank is 4 to 5 m, a height that is determined by the supernatant water level, the filter bed height, and the height of the bottom construction.
In Figure 11 a cross-section is shown of an open rapid sand filter.

The construction of the bottom consists of a false floor with filter nozzles. These filter nozzles have small perforations with a width between 0.5 to 1.0 mm, which prevent the loss of filter sand.
The function of the filter nozzles is mainly to distribute the backwash water and air equally. The height below the filter floor has to have a minimum of 0.5 m for an equal distribution of backwash water and air. In practice, a much greater height is used (1.0 - 1.5 m) because of the desired accessibility of the space for maintenance and cleaning.

Table 1 - Backwash rates for obtaining a specific bed expansion at different temperatures for sand (r_f = 2600 kg/m^3, d = 1.0 mm, p = 0.38)

Temperature	Expansion			
	0%	10%	20%	30%
0	16.2	24.5	33.5	42.8
10	20.2	30.2	41.4	52.9
20	23.8	36.0	49.0	63.0
30	27.7	41.8	56.9	73.1

Backwash troughs are employed above the filter bed in a number of installations for an even collection of backwash water. In a good filter design, equal drainage is possible over a spillway next to the filter bed, even with a horizontal flow length of 5 - 7 m.

The shape of the filter is rectangular with a surface area often between 15 and 40 m^2.
The surface area per filter is mainly determined by the desired number of filters. A minimum of four filters is used because, in maintenance and filter backwashing, a certain production capacity is desired.

When the yearly capacity is 1 million m^3/y, the average production, , is 115 m^3/h and the production on the maximum day is approximately 170 m^3/h (peak factor 1.5). With a filtration rate of 5 m/h a filtration area of 34 m^2 is needed, which is 8.5 m^2 per filter with four filters. With a larger yearly capacity, first a larger surface area per filter will be chosen and then the number of filters will be increased.

It is preferable that every filter is located in its own enclosed space. This will make maintenance possible without microbiological contamination of any nearby filters.

5.2 Operation

During operation the raw water is supplied via valve A (Figure 11), and flows through the filter bed and the filter floor to leave the filter as treated water via valve B. As the filtration continues, the valve in the discharge pipe needs to open further to compensate for the filter resistance caused by deposition of suspended solids. When this regulator is completely open, if continuing the filtration process, the filtration rate and the hydraulic capacity will decrease.
To avoid this, the filter is taken out of service for backwashing.

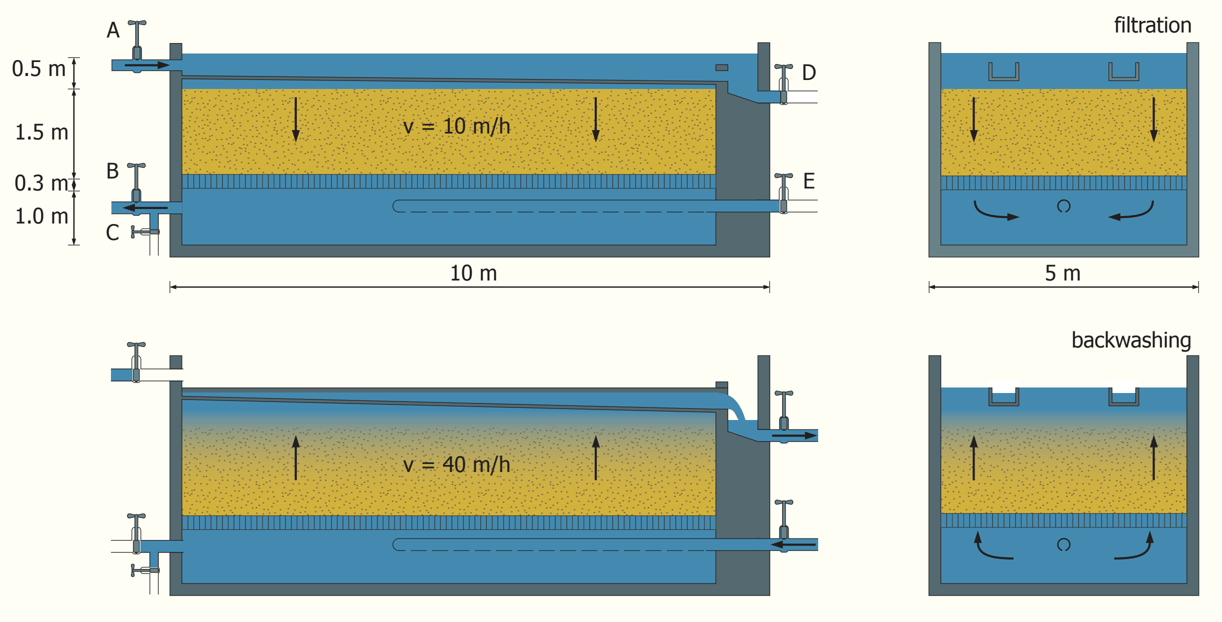

Figure 11 - Construction of an open rapid sand filter

5.3 Backwashing

When a rapid filter is backwashed, the water supply (valve A in Figure 11) is stopped. The supernatant water still filtrates through the bed.
After the filtrate drainage is blocked (valve B), the backwash process is started. That is when valves D and E are opened. The filter is backwashed for a certain period of time with water and air. When the bed is sufficiently clean, the supply of water needed for backwashing is stopped and the wash water drain is closed by valve E.
By opening valve E, the supernatant water filtrates through the bed. Then valve A is opened. Since the water that leaves the filter during the ripening period is generally of poor quality, this water is drained into a waste receptacle.
After the ripening period, valve E is closed and valve B is opened.
The total time that a filter is not in operation due to the backwash procedure varies from 30 to 60 minutes. The backwashing itself lasts approximately 20 minutes.
When the filter run time and the backwash time are known, the net production through the filter can be calculated.

> A filter with a surface area of 80 m^2, a filter run time of 72 hours, and a filtration rate of 5 m/h is backwashed for 20 minutes with a backwash rate of 50 m/h. In addition, the filter is not operating for 20 minutes due to drainage of the supernatant water, and also due to filter the waste.
> The filtrate production is:
> (72-40/60)*5*80=28.533 m^3.
> The quantity of filtrate used for backwashing is 0.333*50*80=1.333 m^3, that is a water loss of 5%.

Over a short period of time, a high wash water flow is needed and it can be supplied through two ways:
- backwash pumps
- elevated water reservoir.

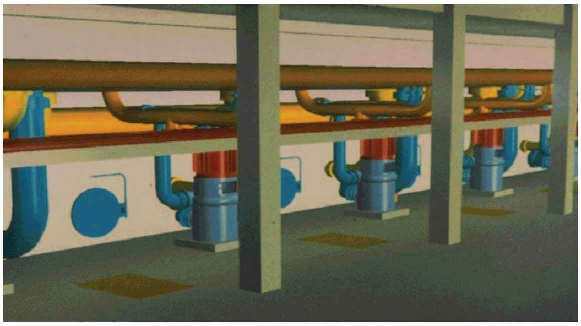

Figure 12 - Discharge pipes for backwash water are the largest pipes in a filter installation

When using backwash pumps, water is obtained directly from the filtrate reservoirs.
During a short period, there is a high energy consumption and, therefore, this is an expensive option. The pipes that transport the wash water from the filtrate reservoirs to the filters are the largest pipes in a water treatment plant (Figure 12).
Assuming that the maximum permitted velocity in a pipe is 1 m/s, it can be calculated that the diameter of the backwash supply pipe to a filter with a surface area of 80 m^2 and a backwash rate of 50 m/h is almost 1.2 meters.
The diameter of the supply pipe for raw water is much smaller. When the filtration rate is 5 m/h, this diameter is 0.35 meter.

When an elevated water reservoir is used (Figure 13), backwash pumps with a lower capacity (10 to 20% of the backwash capacity) can be applied to keep the reservoir continuously filled.
However, there is the disadvantage of the increased investment costs due to the construction of a separated reservoir.

The required pressure for backwash water is around 2-5 mWc. In addition to the static elevation height, most of the pressure losses are due to the resistance resulting from the flow of water through the filter bottom, the filter bed, and the piping system.

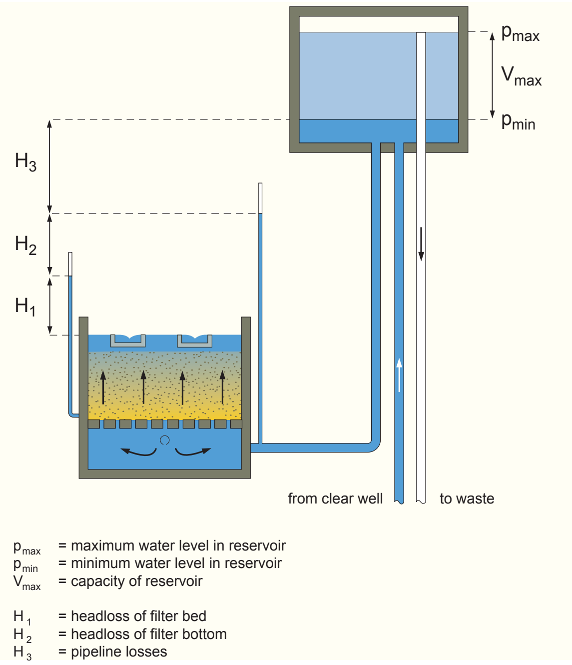

Figure 13 - Elevated water reservoir as backwash system

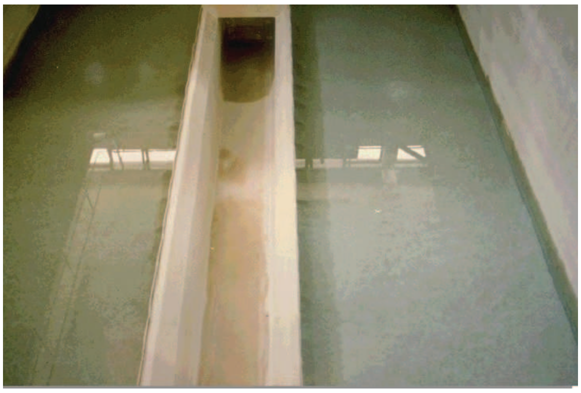

Figure 14 - A central backwash trough

After passing the filter bed, the wash water is drained through a system of troughs (Figure 14 and 15).
The troughs are designed to limit the (horizontal) distance the water must travel after leaving the filter bed.
The moment the water leaves the filter bed, the wash water velocity decreases by a factor of 2.5 and settling in the supernatant water can occur.

The right configuration of backwash water troughs is found by optimization. The more troughs, the higher the investment costs, but the lower the wash water loss is.
In practice, the use of troughs on the sides and at the front are satisfactory and cheap.

In large filters, a “water sweep” (Figure 16) is applied to reduce the volume of backwash water. Raw water is supplied from the sides onto the filter bed, flowing to a central trough, which avoids short-circuits and eddies.

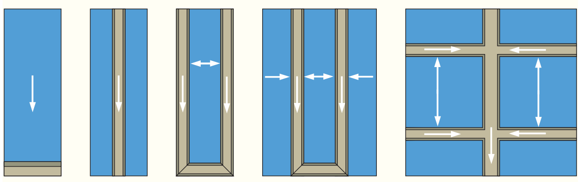

Figure 15 - A central backwash water trough

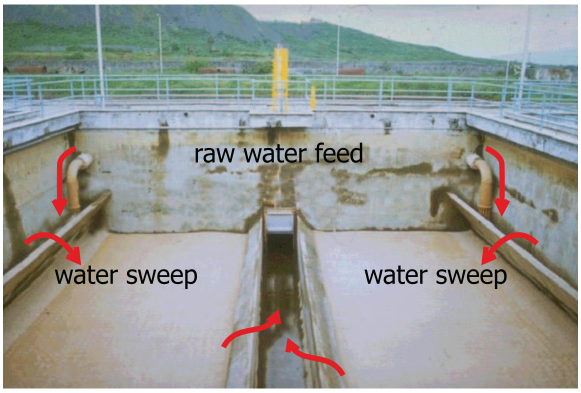

Figure 16 - Water sweep

In the past wash water was drained to waste water ponds, where the solids settled and the supernatant drained to the surface water or sewerage system.

Currently, backwash water ponds are not used anymore due to stricter regulations concerning discharge to surface waters, soil protection and groundwater protection. The backwash water is, therefore, transported to backwash water treatment installations.

In such installations, the backwash water is treated by coagulation-flocculation, followed by the removal of flocs through titled plate separators and rapid sand filters, and a final UV disinfection. The treated water can be recycled into the main treatment process.

An alternative backwash water treatment process consists of micro-/ultrafiltration.

5.4 Filter bottom

After passing the filter bed, the water is drained through nozzles to the filtrate reservoir.

Nozzles are synthetic tubes, incorporated into the filter bottom, which are connected to perforated heads to avoid sand loss. (Figure 17 and 18).

Frequently, a number of support layers of coarse filter material are placed between the filter bottom and the filter bed to enable larger slot sizes in the nozzle, avoiding their clogging..

In addition to draining the filtered water, nozzles also supply backwash water and air.

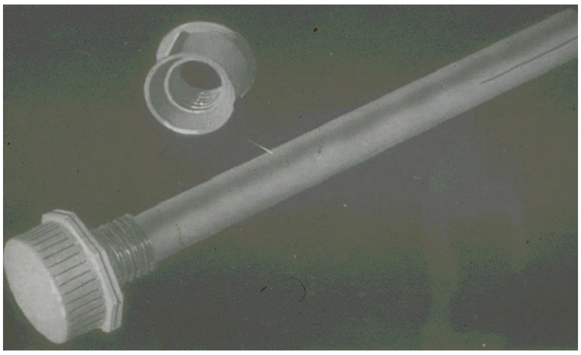

Figure 17 - Nozzle

In order to achieve a uniform distribution of water and air over the filter bed, a considerable filter bottom resistance (0.5-2 m) must be introduced.

5.5 Filter material

The granular material used as medium should have the following characteristics::

- resistant to abrasion (wear)
- free of impurities
- uniform grain-size distribution.

Typically, river sand is applied as filter material. Due to its great variety of grain sizes, the river sand must be sieved before application. The uniformity of the filter material can be expressed through the uniformity coefficient, defined as:

$$U = \frac{d_{60}}{d_{10}}$$

in which:

U = uniformity coefficient (-)

d_{10} = size of sieves that let pass 10% of the

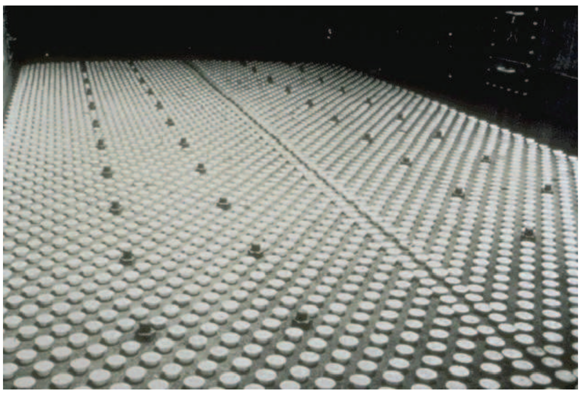

Figure 18 - Nozzle bottom

sand mixture (mm)

d_{60} = size of sieves that let pass 60% of the sand mixture (mm)

If the uniformity coefficient equals 1, the material is uniform. A higher coefficient indicates a larger variety in the grain sizes (Figure 19).
For rapid filtration the value of the uniformity coefficient should be between 1.3 and 1.5 to avoid stratification of the filter bed during backwashing. A lower value of the coefficient is possible, but this results in higher sieving costs and provides little additional advantage.

Other filter materials are given in Table 2.
Filter material with a low density is used when a large diameter is required and the backwash rate is limited.
The heavier filter materials are used during upflow filtration to avoid premature expansion of the filter bed.

5.6 Filter troubles

In spite of rapid filtration being a simple process, many problems can occur.
The choice of the filter material and the design of the filter bottom are crucial.

When the filter material is badly sieved and thus not uniform, stratification occurs during the backwash process. The lighter and smaller grains acumulate at the top of the filter bed, whereas the heavier and larger grains settle on the bottom .
During filtration all suspended solids accumulate in the fine upper layer. This phenomenon is called surface or cake filtration. The cake is difficult to

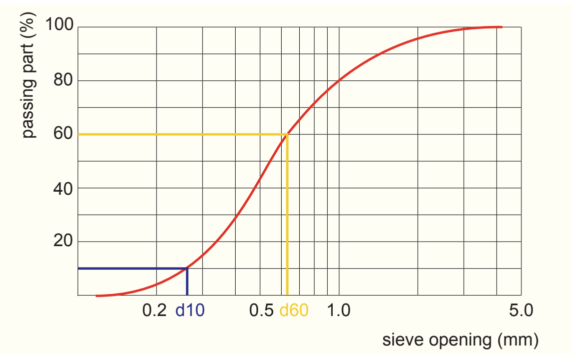

Figure 19 - Sieve curve of filter sand

Table 2 - Density of different filter materials

Filter material	Specific density [kg/m³]
Plastic grains	1,050-1,300
Pumice	1,200
Anthracite	1,400-1,600
Sand	2,600
Garnet	3,500-4,300
Magnetite	4,900-5,200

remove during regular backwash procedures. Cracks are formed in the cake, and preferential flows occur. In addition, mud balls form and settle on the filter bottom, clogging the nozzles.

When a stratified bed is backwashed at low velocities, only the upper layer is expanded (with the small grain sizes). The lower layers are not, or hardly, expanded and, therefore, there is no removal of accumulated solids. With a faster backwash rate, washing out the upper layers can occur.

A non-uniform flow during backwashing (by a poor design or clogging) can lead to preferential flows and disturbance of the filter bed.
This can result in total mixing of the filter material, and support layers that must be situated at the bottom can be found at the surface. This phenomenon is called sand boil.

The filtrate and the wash water must be able to pass through the filter bottom, but filter material must be retained.
The grain size of the filter material is about 1 mm, which means that a small crack in the bottom is large enough for the grains to pass through it and for the filter to become a huge sandglass (Figure 20)
Such cracks can be caused by damage in the nozzle or inaccurate sealing of the bottom plates.

6 Alternative applications of filtration

6.1 Multi-layer filtration

Multiple layer filtration is carried out in a filter bed with various layers of different grain sizes.

Figure 20 - Result of a poorly designed filter bottom

First, the water passes the coarser grains, resulting in a tapered filtering.
In upflow filters, the coarse grains are at the bottom (Figure 21), whereas in downflow filters, the grain size decreases in a downward direction.

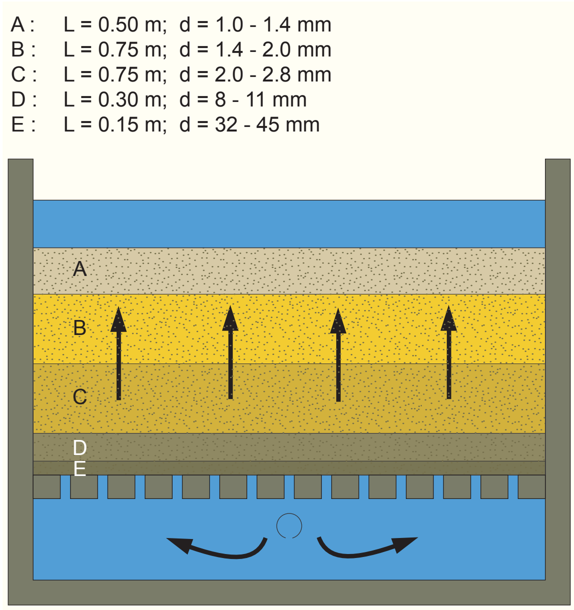

Figure 21 - Multiple layer filtration (upflow filter)

The size and the density are chosen so that the settling velocity of the material in the bed increases in a downward direction and mixing between the two layers during backwashing does not occur.
Usually the filter material is a combination of either:
- a layer of anthracite, which has a large grain size and a low density, on top of a sand layer
- a layer of garnet, which has a small grain size and a high density, below a sand layer.

Multiple layer filtration has the advantage that the larger solids are retained in the top layer of the bed and the smaller ones in the lower parts of the bed.

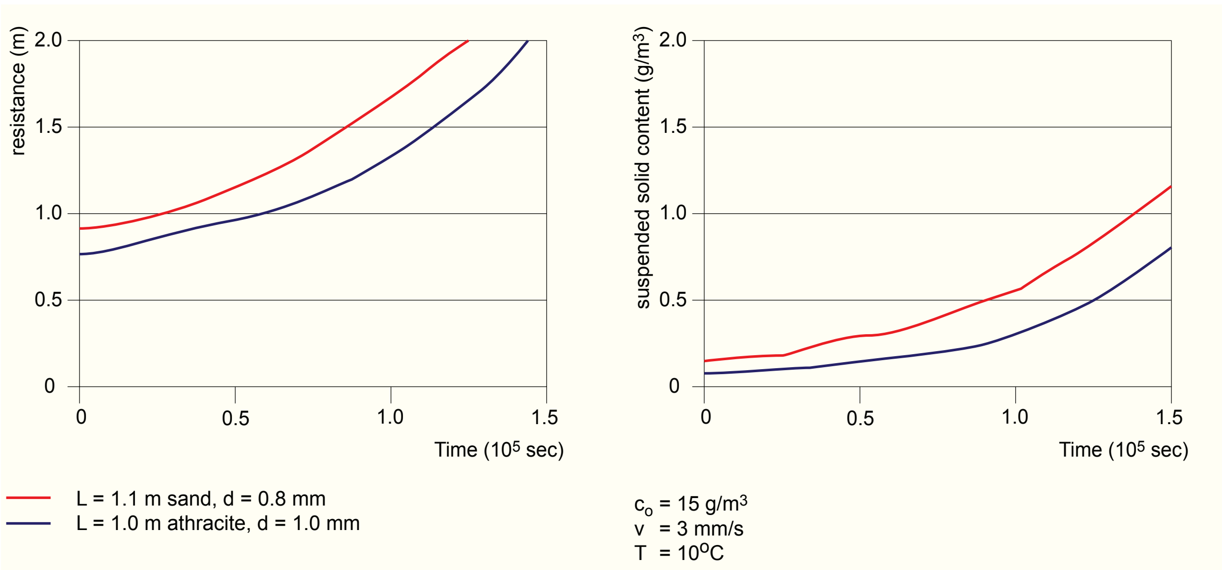

Figure 22 - Difference between single and multiple layer filtration for equal bed heights

Consequently, the increase in filter resistance is spread over the entire height of the bed, resulting in an extended filter run time.
In Figure 22 the progress of the water quality and the resistance are represented for a single layer and a double layer filter bed.
Using the same filtration velocity, the resistance of a double layer bed is lower than in a single layer bed and the effluent water quality is better. Figure 23 shows the resistance build-up for a multiple layer filter.

6.2 Pressure filtration

Pressure filters are based on the same filtration theory as gravity rapid filters but in the former ones the filter bed, the supporting filter bottom and the supernatant raw water are encased in a water-tight steel cylinder. (Figure 24) This results in a closed system, in which the water to be treated passes through the bed under pressure.
On one hand, the high pressure allows a large filter resistance without the danger of negative heads; on the other hand, filtrate pumps are no longer required and the filter can be placed at any random level (Figure 25). Hence, the hydraulic head does not have to be considered.

In addition, the application of a large filter resistance permits the use of high filtration rates with long filter run times (Tr).
The filtration rates normally vary from 7 to 20 m/h, but values up to 55 m/h are possible in pressure filters, thus the surface area of a pressure filter can be small.

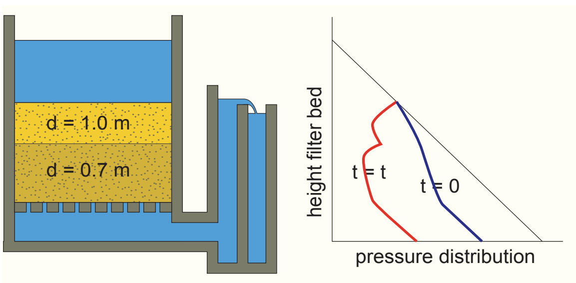

Figure 23 - Resistance build-up for a multiple layer filter

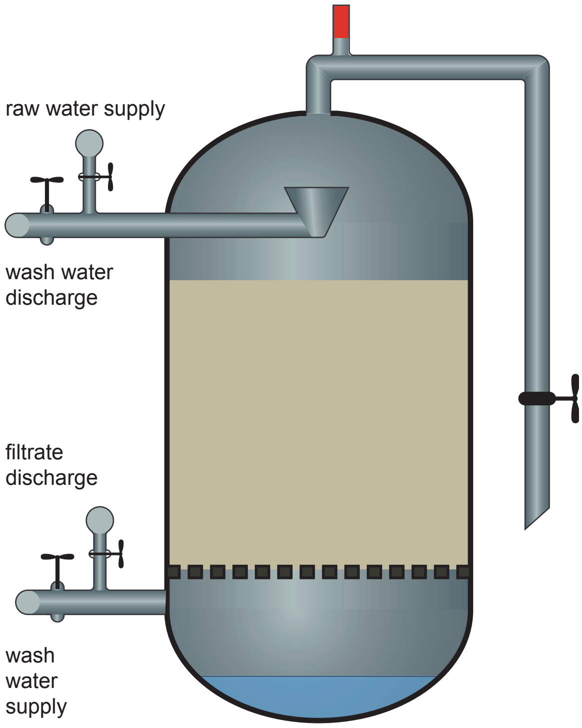

Figure 24 - Principle of pressure filtration

There must be a minimum contact time between the water to be treated and the filtering material, which requires a minimum filter bed height (3 m). Pressure filters are hardly used in drinking water treatment because regular inspections are difficult

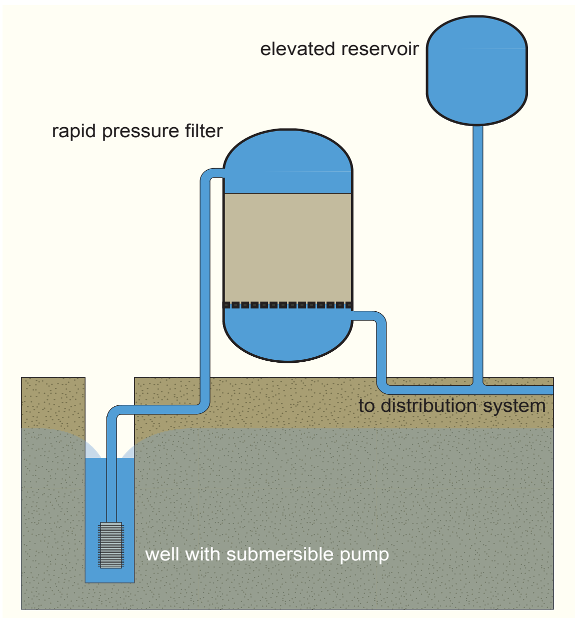

Figure 25 - The filtered water flows without a pumping phase towards the next treatment step

Figure 26 - Cylindrical steel pressure filters

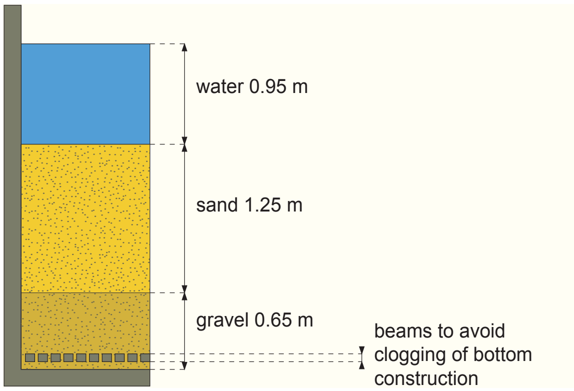

Figure 28 - Principle of upflow filtration

and the systems are rather sensitive. In Industrial water supply, however, pressure filters are widely used (Figure 26).

The diameter of the steel cylinders is 5 m maximum, which results in a maximum capacity of 1000 m^3/h.
When larger capacities are required, a horizontal pressure filter can be applied. This is a pressure filter with a width of 4 to 5 meters and an unlimited length, which results in large surface areas..In practice this length has a maximum of 15 meters.

The height above the filter is determined by the distance between the drainage troughs and the filter bed. This distance varies between 0.4 and 0.6 meters.

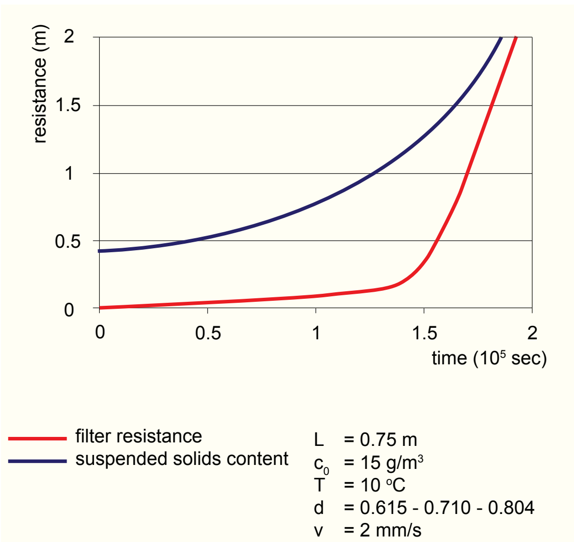

Figure 27 - Changes in quality and resistance of an upflow filter

6.3 Upflow filtration

The best combination of long filter runs and good water quality are obtained when water passes a coarse fraction first followed by a finer fraction of the filter material (Figure 27).
In upflow filtration the coarse material is situated at the bottom and the fine material at the top.
During both, backwashing and filtration, the filter bed is conserved as a result of (natural) stratification (Figure 28).
The elevation height of the water is equal to the hydrostatic water pressure plus the resistance due to flow and clogging. This resistance is the largest in the bottom of the bed (y=L), Figure 29.
Fluidization of sand with a density of 2600 kg/m^3 and a porosity of 40% occurs when the resistance is approximately equal to the height of the filter bed.

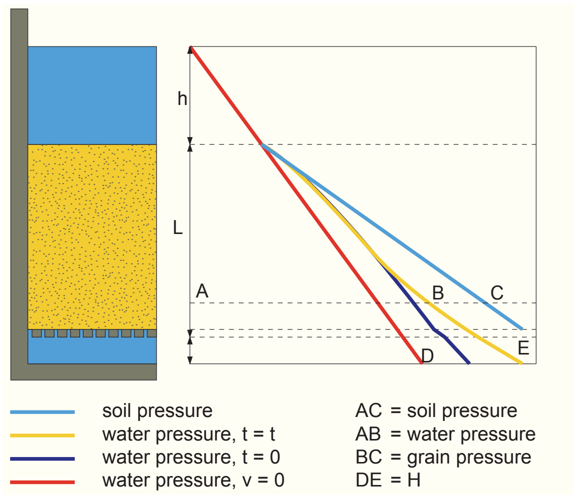

Figure 29 - Pressure distribution in an upflow filter

If fluidization occurs too quickly, a higher filter bed or filter material with a higher density can be applied.

Despite of the good effluent quality that can be obtained, upflow filtration has several disadvantages:

- wash water and filtrate are drained through the same trough. This increases the risk of contamination of the filtrate
- fluidization of the top layer of the filter bed can occur, resulting in a washing out of filter material, diminishing the filter bed height and lowering the removal efficiency
- raw water is uniformly distributed by nozzles in the bottom of the filter. The nozzles can become clogged by impurities in the raw water, resulting in extra resistance and a non-uniform distribution of water over the filter bed.

6.4 Limestone filtration

Limestone ($CaCO_3$) filters are filled with grains of calcium carbonate or half-burned dolomite. When aggressive water (with high levels of carbonic acid) passes these filters, the concentration of carbonic acid will decrease and the levels of hydrogen carbonate and pH will increase.

Water that is not in (calcium-carbonic acid) equilibrium dissolves limestone grains according to the reaction:

$$CaCO_3 + CO_2 + H_2O \longleftrightarrow Ca^{2+} + 2.HCO_3^-$$

Since the limestone grains are dissolved, they need to be replenished regularly.

Normally, replenishing is executed when 10% of the limestone is used. If limestone filtration is used in groundwater treatment after aeration, ferric and manganese removal and nitrification can occur in the filter.

6.5 Continuous filtration

In continuous sand filtration, the backwash process is made continuously by constantly recirculating and purifying sand through a central pump.

In a continuous filter, the water flows in an upward direction, and the transport of sand occurs in a downward direction (Figure 30). The inlet of raw water (with impurities) is at the bottom of the filter. At the top of the filter the water flows over a weir and is transported to the next treatment processes.

The sand retains the impurities. By means of a sand pump (mammoth pump), the lowest layers of sand are removed from the filter and brought to a sand washer that is situated above the filter. The sand washer removes the impurities from the sand and the clean sand is supplied on top of the continuous filter.

Due to the continuous removal of impurities, the quality of the filtrate, the bed resistance and the pressure distribution in the filter are constant and time independent. The filtration rates of a continuous filter vary from 14 to 18 m/h.

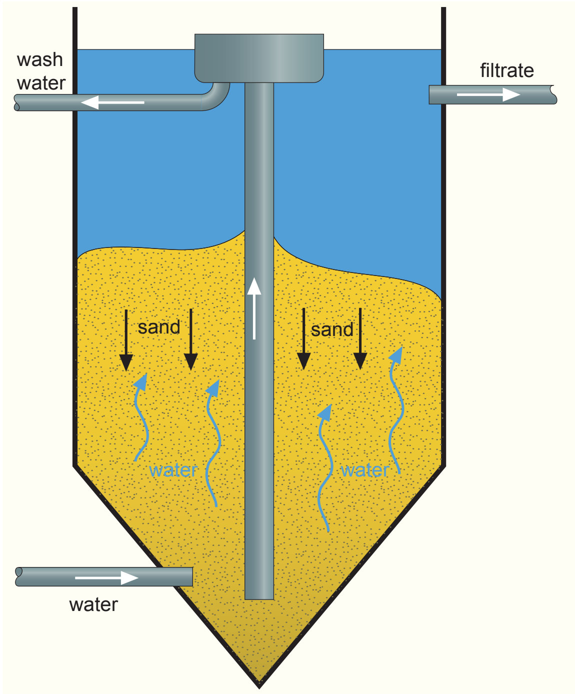

Figure 30 - Schematic representation of a continuous filter

Comparing to a discontonuous sand filter, the advantages of a continuous filter are:
- continuous filtration process
- continuous wash water flow
- less accumulation of sludge.

And the disadvantages are:
- large wash water flows
- sand wash installation is in direct contact with filtrate, resulting in contamination risks.

6.6 Dry filtration

Dry filtration is used when the water contains a high ammonia concentration, so it is used for the treatment of river bank and groundwater.
The oxidation of ammonia into nitrate requires large amounts of oxygen: 3.55 mg/l O_2 per mg/l NH_4^+. The oxygen concentration of water is approximately 10 mg/l. Hence, in water with ammonia concentrations larger than 2.5 mg/l, nitrification will be incomplete.
Dry filtration has no supernatant water level. The water to be treated flows in a downward direction through a bed of granular material, accompanied by a downward or upward flow of air of about the same magnitude. A continuous gas transfer between air and water takes place. The oxygen consumed during the treatment can be replenished directly by the accompanying air. The formed car-

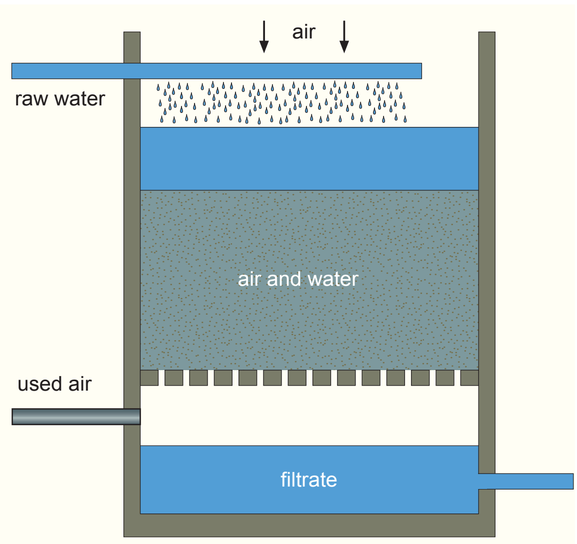

Figure 31 - Schematic representation of a co-current filter

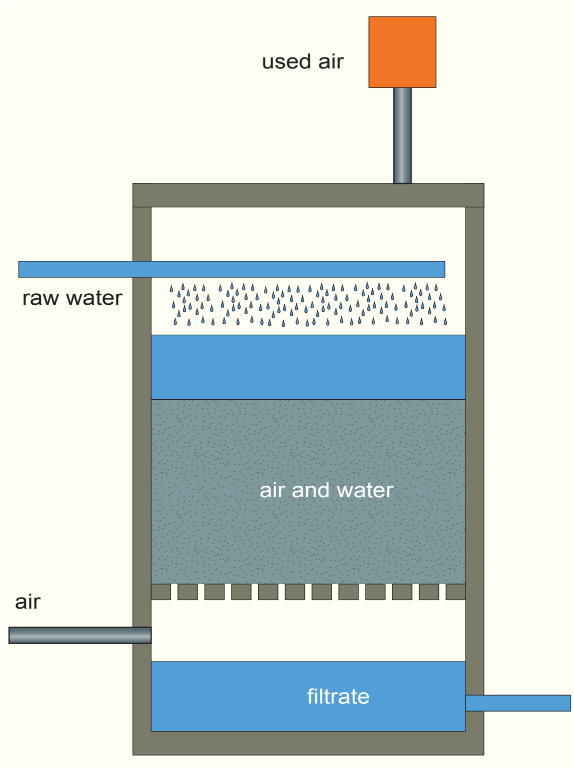

Figure 32 - Schematic representation of a counter-current dry filter

bon dioxide is removed from the water. The pores are only partially filled with water and, thus, the velocity of the water through the pores is greater than in (wet) filtration. The flow through the pores is turbulent promoting the hydrodynamic transport of impurities from the interstitial water to the grain surface where they attach.

The filtered water is collected below the filter bottom and flows via gravity to the next treatment process. From the filtrate chamber, air is continuously pumped by a ventilator maintaining a (forced) simultaneous flow of air through the filter bed (Figure 31). When, in addition to oxygen transfer, the dry filter is also used for gas stripping, a counter-current flow of water and air can be used in the filter (Figure 32).

Spray nozzles are used to obtain a uniform distribution of the water over the filter as well as to improve the gas transfer (addition of oxygen and removal of methane and carbonic acid).
A dry filter does not only remove ammonia, but also iron and manganese. In the top layer of the

filter bed (depth of 0.5 to 1.5 m) iron removal takes place. After completion of this process, manganese and ammonia removal occurs more or less simultaneously. Dry filters are often followed by wet rapid filters, in order to remove the bacteria formed during dry filtration

6.7 Slow sand filtration

Slow sand filters are suitable, as an alternative to chemical disinfection, when the most important objective is to remove bacteria and viruses.
The filter material has a small grain size (e.g., 0.2 to 0.6 mm) and the filtration rate is below 1 m/h.
For treatment of the same water flow, a larger filtration surface area is needed than that used for rapid filters. This is illustrated in the aerial picture

Figure 33 - Difference in surface area between rapid filtration(orange) and slow sand filtration red)

of the treatment plant at Leiduin (Figure 33).

Filtration occurs mainly in the top layer of a slow sand filter, where a biologically active "Schmutzdecke" is formed.
To clean the filter, backwashing cannot be applied. Instead, the upper sand layer (usually 1 cm) is scraped off.

Slow filters are normally placed at the end of the treatment line, which means they are barely loaded with impurities and the filter run time can have an order of magnitude of several years.