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Pumping station of Harderbroek Improving iron removal

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1. Introduction

The pumping station of Harderbroek is situated in Flevoland, in the south west of the Netherlands.

Flevoland is the biggest polder in The Netherlands, since the earliest 30s the water has been pumped out to dry the land and therefore this zone is under the water level.

The drinking water in all the region is provided by three pumping stations: Harderbroek, Fledite and Bremerberg.

These are situated in the furthest area from the coast in order to extract freshwater from a lower depth. In fact near the coast the interface of salt-fresh water is deep, whereas it is closer to the subsurface going inside the land. This is the reason why the pump plants are far from the distribution points. In fact it is cheaper to have longer distribution pipes than to dig deeply or to desalinize the water from the sea.
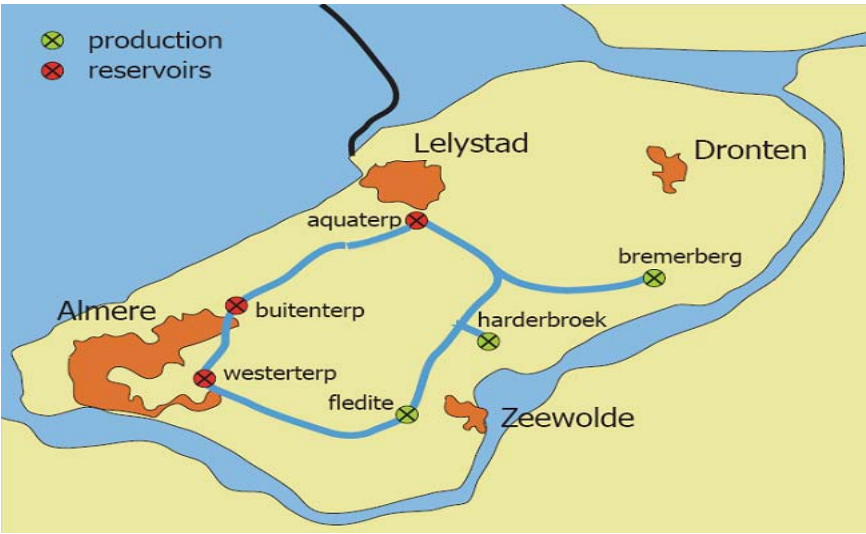

Figure 1.1: The location of the pumping stations and of the reservoirs in the region of Flevoland.
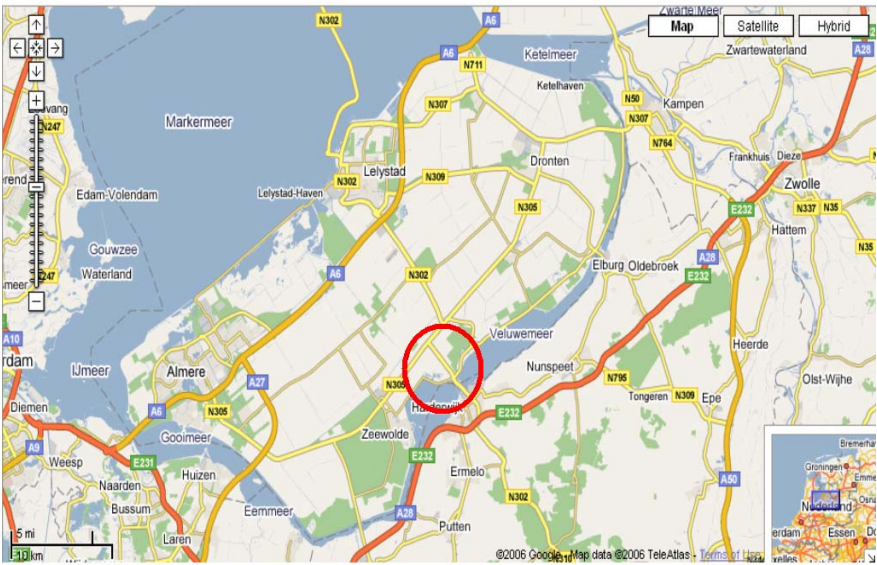

Figure 1.2: The region of Flevoland (from GoogleMap).

The quality of the water coming from this zone is very good, the only problem is the high concentration of iron and manganese, which is not a relevant matter for human health, but it can be for the organoleptic characteristics (the colour, the taste, etc.) and it can disturb the activities that we usually do with water (cleaning, washing, etc.).

		gezamenlijk ruwwater pompstation Harderbroek		
		gemiddeld	minimum	maximum
tempratuur	°C	12,9	12,0	13,0
zuurstof	mg/l	0,705	<0,500	1,000
zuurgraad		7,47	7,42	7,50
EGV 20 °C	mS/m	16,4	16,2	16,6
waterstofcarbonaat	mg/l	84,9	83,4	87,5
chloride	mg/l	7,50	7,23	7,67
sulfaat	mg/l	8,44	8,28	8,74
natrium	mg/l	6,39	6,31	6,48
calcium	mg/l	25,8	25,5	25,9
magnesium	mg/l	2,07	2,06	2,11
totale hardheid	mmol/l	0,729	0,721	0,734
ammonium	mg/l	<0,040	<0,040	0,061
nitriet	mg/l	<0,0070	<0,0070	<0,0070
nitraat	mg/l	<0,50	<0,50	<0,50
ijzer	ug/l	1400	1360	1500
mangaan	ug/l	122,0	121,0	123,0

Tab 1.1 : Measured concentrations in the raw water which enters the plant.

Harderbroek plant is in operation since October 1997 and it is operated by Vitens which is the main drinking water company in The Netherlands.
Vitens has decided to improve the efficiency of the plant to decrease the iron concentration and improve the quality of the clean water. In fact the costumers have complained about the colour of the water. The temporary solution that has been found to soften the problem consists of cleaning the pipes with a higher frequency, but the costs of this operation and the campaign to warn the people are quite high. Furthermore the company doesn't want to lose reliability for the costumers.
The purpose of this project is to modify or change the actual treatment to improve the iron removal.

2. Existing plant

The water, as the ground water in general, is very soft and aggressive, with high content of iron and manganese, therefore the treatment consists of aeration and filtration steps. The water coming from the wells is collected in a first reservoir to soften the peaks. From that it is pumped to the cascades and then by gravity to the rapid sand filtration. After this the water is pumped again to the tower aeration and then goes to the reservoirs and to the distribution pipes.
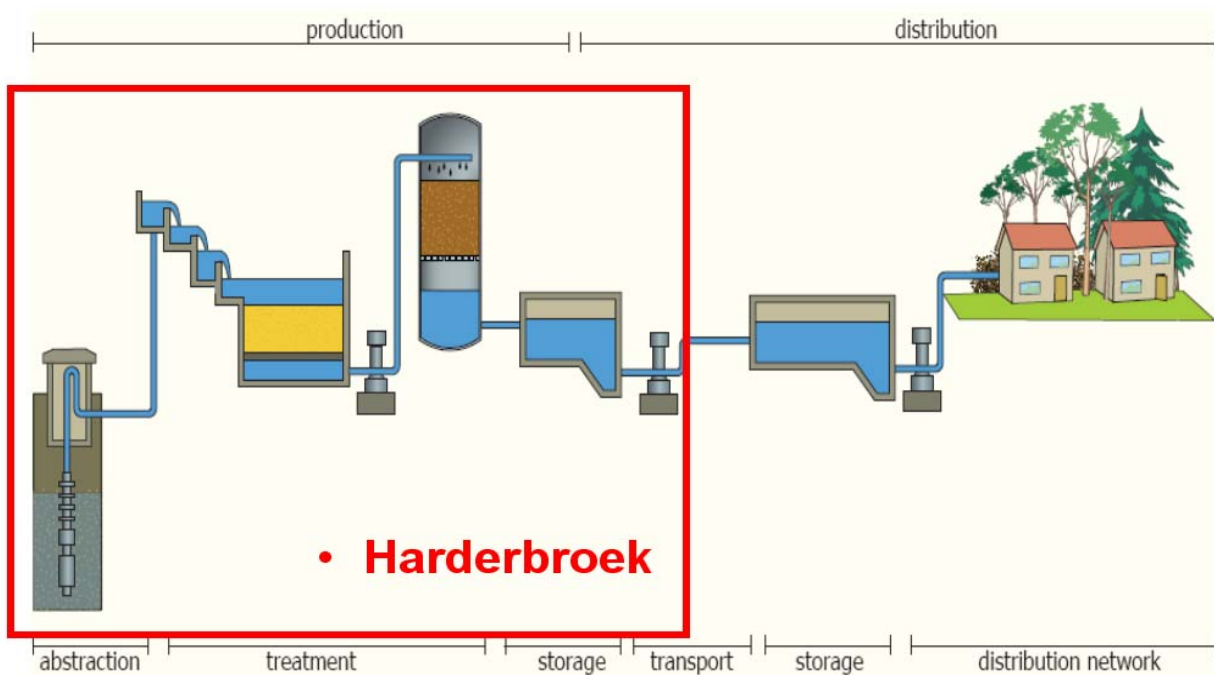

Figure 2.1: Harderbroek treatment scheme

2.1 Treatment scheme

Here it follows the description of each step of the treatment scheme:

Abstraction: For the abstraction of water from the underground 10 wells have been built. Each well has a capacity of 200 m³/h. Groundwater is caught from 120/170 m below the

earth surface through 14 fixed pumps and 2 frequency pumps. The frequency pumps are necessary to regulate the flux entering the plant on the basis of the level of the clear water reservoir.

Cascades: The water pumped from underground enter the room with the cascades. This kind of aeration system has been chosen because it is more difficult to clog (it can be considered not sensitive to deposits of iron) and it is an open one. This is a great advantage, in fact the water treated at Harderbroek is very rich not only in iron but also in CO_2, therefore it needs a process which allows it to strip. Beside this, it is a cheap system. There are 4 cascades in the plant with 6 steps each. Two lines are provided for the plant, hence two cascades are operating continuously while the other two, which are separated by a wall, are working just if there is a big request of water or if the principle line is out of order. The maximum capacity of each cascade is 450 m^3/h. The efficiency of the system for the CO_2 removal is quite low: it is possible to achieve only about the 10-20% for each step.

Figure 2.2: View of one of the cascades with two filters.

Rapid sand filtration: Each cascade leads to two filters, therefore Harderbroek plant has a total of eight filters. Each one has a maximum flow capacity of 250 m^3/h and the maximum filtration rate is 10 m/h. The sand bed has a height of 2 m and below it nozzles are present in order to operate the backwash. The backwash cycle consists of fluxes in counterflow of water and air and it starts after filtering 8000 m^3.
The backwash water is collected and treated with ferric chloride.

Tower aeration: The removal of iron is oxygen consuming and it lowers the pH, for this reason it is necessary another aeration system after the treatment.
There are three towers each one with a maximum capacity of 320 m^3/h. The towers are completely filled with packing material to increase the contact surface.

Figure 2.3: In this picture is represented one of the tower aerations present in the plant of Harderbroek. It is located in a room above the filters and it is receiving the water by means of a pump.

The water that has been treated through this steps is then stored in a clear water reservoir before being delivered to the users.

2.1 Drinking water standards

In the Netherlads the drinking water standard for iron concentration is 200 μg/l. But as we can see from the tab 1, the iron concentration in the raw water is very high, therefore the efficiency of the plant must be high as well.

The iron concentration which is now achieved is 40 μg/l that is below the standard and the Verwin recommendation (50 μg/l), but it is still above the 10 μg/l recommended by Verberk. This means that still post-flocculation of soluble iron can occur in the reservoir or in the pipes of the distribution network.

3. Problem definition

Even if the general quality of the water is satisfying because it meets the required standards values, the residual concentration of iron can still be a problem. In this case various complains by the costumers have been received by Vitens, in fact the settled iron can give to the water a typical rusty colour due to iron particles which are not considered toxic but are annoying in the domestic activities.
Some research has been carried on to find out the cause of the problem and to improve the efficiency of the plant.
Several experiments have been carried out in a pilot plant. It has been built inside Harderbroek pumping station and it consists of a column that reproduces the filtration process. Some parameters can be modified through a control panel.


Figure 3.1: Pilot plant built inside Harderbroek

3.1 The mechanism of iron removal

In anaerobic conditions the iron is present in the water especially as ferrous iron, Fe^{2+}. The rapid sand filtration is used to remove iron flocks. In order to remove Fe^{2+} it has to be oxidized to ferric iron, Fe^{3+}. This means that it is necessary to restore a sufficient level of oxygen in the groundwater. Because of its low solubility, iron (III) will hydrolyze to form flocks that will be then removed with filtration.
The reaction (1) takes place

$$4Fe^{2+} + O_2 + 2H_2O + 8HCO_3 \rightarrow 4Fe(OH)_3 + 8CO_2 \qquad (1)$$
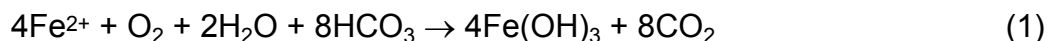
Here above both the processes of oxidation and hydrolysis are visible.
It is important to notice that the higher the pH is and the more the oxidation rate of iron (II) increases. Besides this the reaction is oxygen consuming and pH lowering (this is the reason why there are tower aerators at the end of the treatment).

3.2 The cause of the problem

After having investigated the whole process, the main cause of the problem has been found in the low pH of the water. In fact the cascades are not a high efficiency aeration system, this means that the pH is not raised enough because there is still a big quantity of CO_2 in the water.

$$CO_2 + H_2O \rightarrow H_2CO_3 \tag{2}$$
$$H_2CO_3 \rightarrow H^+ + HCO_3^- \tag{3}$$

For this reason the conversion of the ferrous iron into ferric iron is not quick and complete. Therefore a part of the iron remains soluble and will not be removed by filtration. This soluble iron (ferrous iron), as the pH increases again, will be oxidized into iron (III).This is what happens in the tower aeration where it will start to flocculate. It will cause the settling in the reservoir or in the distribution system.

4. Alternatives

The purpose of the alternatives which will be developed is to obtain a high pH before or eventually during the filtration in order to avoid that soluble iron remains in the water causing problems in the following phases.

Four main alternatives are considered:

1. Construction of eight filters of limestone
2. Use of the half of the existing filters for limestone filtration
3. Improving the aeration system
4. Changing the aeration system
5. Addition of chemicals

With the possibilities 1, 2 and 5 an higher pH is achieved by adding some kinds of substances to the water, whereas in the others the pH is raised by using a more efficient aeration system in order to strip a bigger amount of carbon dioxide.

4.1 Construction of eight filters of limestone

A possible treatment for aggressive water with an high content of iron in the dissolved form (Iron (II)) is the limestone filtration. In fact the rapid sand filtration can efficiently operate in the removal of iron (III), in fact it can easily form hydroxides which are hence stopped by the grains.
In marble filtration, the filter medium consists of calcium carbonate grains. In the filter the oxidation and hydrolysis of iron take place and it is described by equation (4).

$$4Fe^{2+} + O_2 + (2n+12)\ H_2O \leftrightarrow 2(Fe_2O_3\ nH_2O) + 8H_3O^+ \tag{4}$$
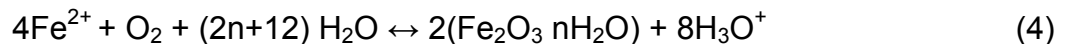
The rate of reaction is mainly determined by the oxygen concentration and by the pH of the water. The iron oxidation takes place mainly in the uppermost part of the filterbed. The hydroxide flocks have a catalytic action on the iron oxidation therefore the conversion is realized especially in the first decimeters. This is accompanied by a drop in pH resulting from the acid production, this results in the conversion of bicarbonate to CO_2 according with reaction (5).

$$H_3O^+ + HCO_3^- \leftrightarrow 2H_2O + CO_2 \tag{5}$$

The acidity removal reaction which takes place in the marble bed is shown below.

$$CaCO_3 + CO_2 + H_2O \leftrightarrow Ca^{2+} + 2HCO_3^- \tag{6}$$

Due to the pH-increase which occurs in this acidity removal process it is expected that iron removal will be more rapid in a marble filter compared with a sand filter.

For the iron oxidation and flock formation the pH is a very important parameter: a low pH decrease the reaction rate. The experiments done in the pilot plant inside Harderbroek show that a pH of 8 can be obtained with marble filtration. In this case the oxidation of iron (II) in iron (III) is faster (around one minute) and then iron (III) will quickly hydrolyze to form hydroxide flocks.

The limestone grains used are Aquaperles grains, produced by a company specialized in drinking water treatment. A cheaper solution could be to use the pellets from a softer reactor, which are covered by Calcium Carbonate.

Treatment scheme

The treatment scheme in this case consists of the cascades as first step, then the water goes, by gravity, in the limestone filters. From here it is pumped to the tower aeration, then it flows towards another building where there are the rapid sand filters. After the limestone filters the pumps have to give enough hydraulic head to assure the water the energy to go through the towers aeration and the filters. The filters have to be built in an other building because there is no space in the plant. The second filtration step is done to remove the residual flocks and it can be used as a polish filter with smaller grain size than the actual one.
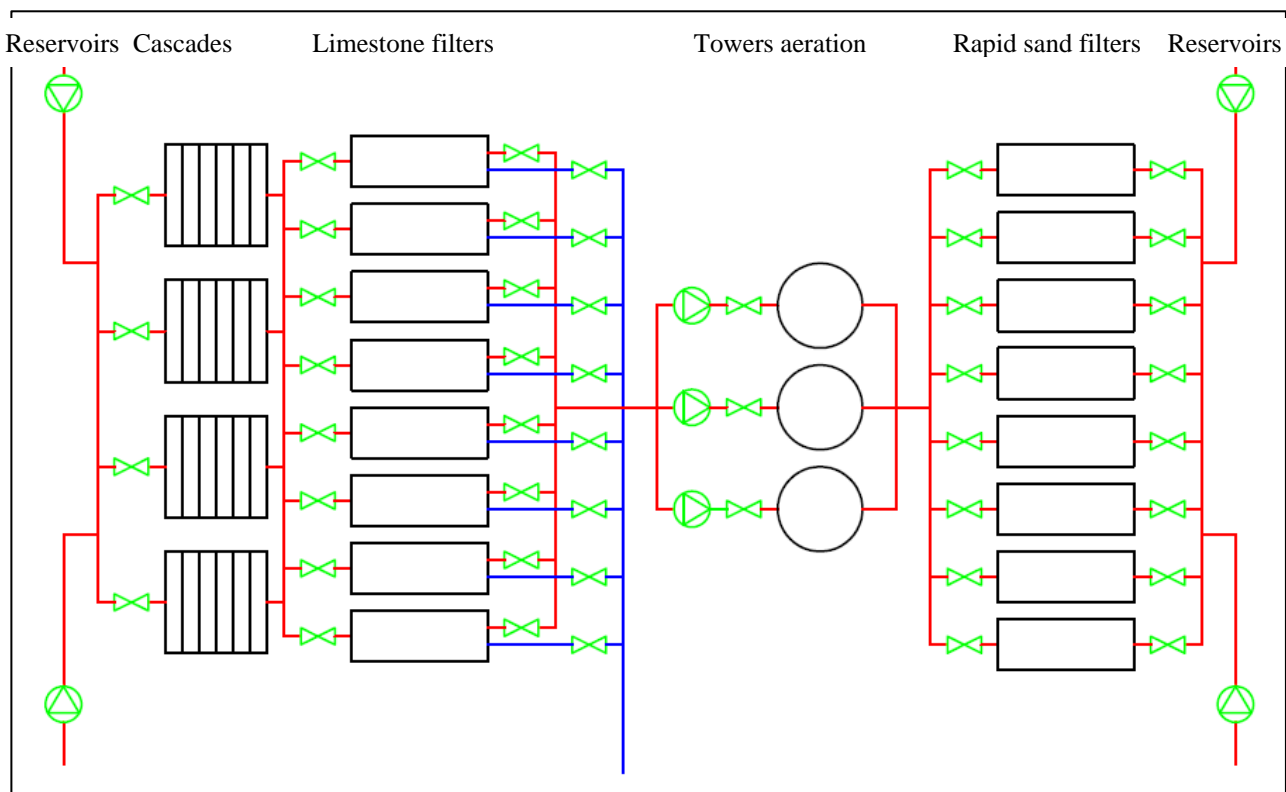
Reservoirs Cascades   Limestone filters   Towers aeration   Rapid sand filters   Reservoirs

Figure 4.1: Process scheme of the alternative number 1

Design parameters

The considered flow for the design is the maximum flow 1800 m^3/h. Only seven filters will run at the same time so the flow in each filter is up to 225 m^3/h. This is the amount of water that arrives in the system in peak situations.
Considering that the surface of each filter is 24 m^2 the maximum filtration rate in each filter will be V_F= 9.4 m/h.
To calculate the speed of reaction (6), the data from an experiment with a filter of Suriname shells have been taken. These shells are also made of calcium carbonate but in a lower percentage compared with marble grains. The reaction is almost complete in a range of 2 minutes. The porosity of the bed is 35%.

The minimum bed height has been calculated with the filtration rate and the reaction time:
Min bed height = $(t_R * v_F)/n$ = 2/60 (h) * 9.4 (m/h) / 0.35 (-) = 1 m
It has been decided to keep the actual bed height (2 m) and to increase it of 20%, this means that it becomes 2.4 m: when the volume corresponding to this surplus of 0.4 m will be consumed new grains will be added. This is an easy criterion to control the consumption of the limestone grains.

The outflow from the cascades has a pH around 7.46. The pH of the raw water is raised because of the CO_2 removal but at the same time is lowered because of the flocks formation reaction, therefore the final pH is not much more different from the initial one.
A pH of 8 can be obtained with the limestone filtration if a ratio of 1:50 between CO_2 and HCO_3^- is achieved.
The initial concentration of bicarbonate in the raw water is 0.705 mg/l that corresponds to 1.4 mol/l. The concentration of CO_2 after the cascade is 5.5 mg/l that corresponds to 0.125 mml/l. To obtain the required ratio (1:50) it would be enough to reach a concentration of CO_2 around 0.03 mmol/l, but to have a certain safety value it has been decided to remove all the concentration of CO_2 (0.125 mmol/l = 5.5 mg/l). This is reasonable also because it is not possible to calculate the CO_2 that is formed in reaction (5) because we don't have enough data of the iron concentration.
From reaction (5), it can be seen that 1 mmol of CO_2 reacts with 1 mmol of $CaCO_3$ hence it is possible to calculate the amount of $CaCO_3$. In this case the average flow has been considered (800 m^3/h). The average flow in each filter is 100 m^3/h.
The amount of $CaCO_3$ used is:
$CaCO_3$= Qavarege (m^3/h) * 10^3 (l/m^3) * $CaCO_3$ (mmol/l) * PM $_{CaCO3}$ (mg/mmol) / 10^6 (kg/mg)
= 100 * 0.125*100/10^3= 1.25 kg$CaCO_3$/h

Considering the density of calcium carbonate (2.7 kg/m^3) the volume occupied by the removed mass has been calculated:
$CaCO_3$ (m^3/h) = $CaCO_3$ (kg/h) / density = 1.25 (kg$CaCO_3$/h) / 2.7 (kg/m^3) = 0.5 m^3/h
As stated before, it has been chosen to purchase the Juraperles grains from the Aquatechniek company, that have a purity of 99.1% and a diameter of 1.2-1.8 mm. The high degree of purity allows us to consider the $CaCO_3$ removal rate still 0.5 m^3/h.
It is useful to know how much time it will take to consume the volume correspondent to 0.4 m (the 20% of the initial bed height), because it is the time to replace the grains
Time of replacing the grains = volume (20%height) / removal rate of $CaCO_3$ = 9.6/0.5=19.2 h.
It is possible to conclude that the filter material has to be replaced every 19 hours.
This time seems to be very short, additional experiments are required to confirm it.

The limestone grains storage tank has a capacity of 3 months, in this way the material transport costs can be not too high (4 times for year) and the construction costs too. So the total volume of the storage tanks have to be 1080 m^3.

The hydraulic head that is given to the pumps after the limestone filters considers the height of the tower and the height of the filters, increased of the losses on the pipes (Appendix)

Backwash

There are several criteria to backwash the filter. The criterion used to backwash the actual rapid sand filter is measuring the amount of filtrate (8000 m^3/h takes around 32 hours). To

backwash the limestone filters and the new rapid sand filters it has been decided to continue to use the same criterion. The required bed expansion is 20% that bring a new porosity of 46%. The backwash is done with water and air flow. There are two phases, in the first one there are air and water, instead in the second one there is only air.
The following table gives an indication of the water and air flows during the two phases.

Table 4.1: Water and air flows and their duration during the backwash of the limestone and the rapid sand filters

	Q water [m3/h]	Q air [m3/h]	Time [s]
1st phase	600	900	750
2nd phase	300	-	870

A more precise system to start the backwash could be to look up when the level of the water over the filter bed increases more than a certain value. If this happen it means that the resistances in the bed are too high and the filter has to be backwashed.

Costs

The costs can be divided in construction costs and in management costs.
The construction costs are due to the building of the 8 filters, of the storage tank for the limestone grains and the new pumps. Two to connect the 8 new rapid sand filters with the clean water reservoirs, and two to connect the 8 limestone filters with the limestone grains storage tank. Of course the pipes that connect the different parts have to be considered in the constructions costs.

The management costs include the cost of the Juraperles grains, the grains transport costs and the costs for the energy consumed by the pumps.

Only the constructions costs will be analyzed using the costs manual.
Storage of limestone: made of sheet steel zinc-coated: 3 m^3 cost 1600 euro, in our case the volume is 1080 m^3, therefore it costs EUR 576000.
Rapid send filtration: approx. EUR 3,5 millions

Results

The use of limestone filtration allows to obtain a lower concentration of iron (III) although the column experiments only showed a small change in total iron removal.

The use of limestone filtration causes, beside the wanted effects, some changes in the quality of the water regarding the hardness and the buffering capacity.
The total hardness of the raw water (0.729 mmol/l, see Table 1) is quite low, this means that it is an aggressive water, and in fact it is classified as quite soft water (see table 3). After the limestone filtration the hardness increases a little due to Ca^{2+} (0.854 mmol/l) but continue to stay in the quite soft category.

Table 4.2: Classification of the water depending on the hardness

	very soft	quite soft	soft	quite hard	hard	very hard
mmol/l	< 0.5	0.5 – 1.0	1.0 – 1.8	1.8 – 2.5	2.5 - 5	> 5

The buffer capacity increases due to the production of bicarbonate. In fact for each mole of $CaCO_3$, 2 mol of HCO_3^- are produced.
The initial concentration of HCO_3^- = 1.39 mmol/l but it becomes 1.64 mmol/l after limestone filtration. The minimum concentration in the water of HCO_3^- is 1 mmol/l but the preferable value is 2 mmol/l and after the limestone filtration the concentration of bicarbonate gets closer to the preferable one.

Another improvement of the final effluent is due to the final rapid filtration with a smaller grain size medium (0.6-1 mm) than in actual rapid sand filters. This allowes to obtain a better effluent quality but to have more information about how much is the improvement more analysis of the suspended solids in the outflow have to be done.

4.2 Use of the half of the existing filters for limestone filtration

The second alternative is similar to the first because the removal of iron is improved using limestone filtration.

Treatment scheme

After the cascades the water flows to the limestone filtration and then to the tower aeration and to the rapid sand filtration.
The filters used for limestone filtration are 4 and the other 4 are used for rapid sand filtration. In each room there will be two consecutive limestone filters and two consecutives rapid sand filters, in this way the system has two parallel lines in case one is broken.
The decision not to built eight new filters but to have only four has been taken looking at the situation in the plant. In fact the amount of water treated has never required more than four filters, most of the time the filters used were only two. The maximum flow , on which the plant has been built, has never been reached. Nevertheless to satisfy an eventual increase of the water demand it is possible to built a reservoir before the plant. In this way the more water needed can be extracted, stored, treated and stored again in a clean water reservoir to satisfy the peaks.
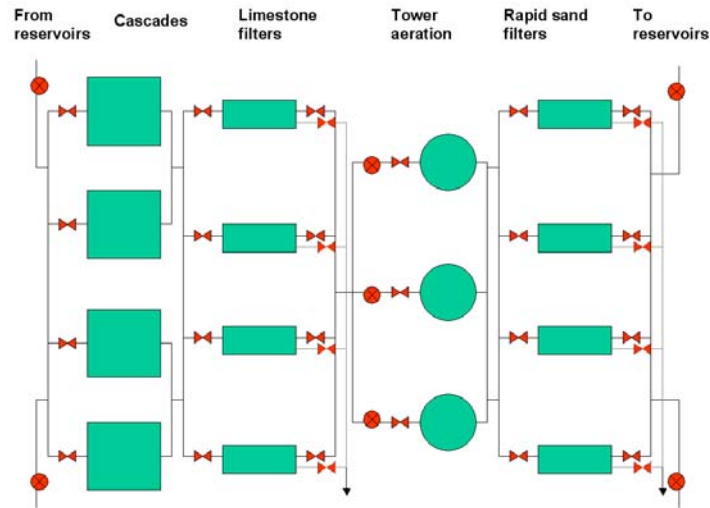
Figure 4.2: Process scheme of the alternative 2

Design

The considered flow to determine the filtration rate and consequently the bed height is the average flow of 800 m^3/h, hence each filter has a flow of 200 m^3/h. The filtration rate is 8.3 m/h. Knowing that the reaction time is 2 minutes and the porosity of the bed is 35% the minimum height of the limestone bed is 0.7 m. In this case it has been chosen to kept the height of the actual filters (2 m) increased of a 20 % more, 2.4 m.
The amount of $CaCO_3$ used is:
$CaCO_3$= Qavarege (m^3/h) * 10^3 (l/m^3) * $CaCO_3$ (mmol/l) * PM $_{CaCO3}$ (mg/mmol) / 10^6 (kg/mg)
= 200 * 0.125*100/10^3= 2.5 kg$CaCO_3$/h
Considering the density of calcium carbonate (2.7 kg/m^3) the volume occupied from the removed mass has been calculated:
$CaCO_3$ (m^3/h) = $CaCO_3$ (kg/h) / density = 2.5 (kg$CaCO_3$/h) / 2.7 (kg/m^3) = 0.9 m^3/h
It is useful to know how much time it will take to consume the volume correspondent to 0.4 m (the 20% of the initial bed height), that is the time to replace the grains in the filter.
Time of replacing the grains= volume (20%height) / volume consumed of $CaCO_3$ = 9.6/0.9=11 hours. Every 11 hours the filter material has to be replaced.

The limestone grains storage tank has a capacity of 3 months, in this way the material transport costs can be not too high (4 times for year) and the construction costs too. So the volume of the storage tanks has to be 1885 m^3.

The reservoirs have to be built to guarantee that an eventual peak at the maximum flow can be treated. If the demands of water will increase, more water can be extracted and stored in the reservoir. After been treated it can be stored in the existing clean water reservoirs, ready to be used in critical situations.

Also in this case the hydraulic head that the pump has to give t the water has to be enough high to arrive and go through the other filters. The pipes from the aeration towers have to arrive under the channel that connect the cascades to the filters. The pipes that connect the four rapid sand filters with the cascades have to be disconnected.

Backwash

To backwash the limestone filters and the rapid sand filters it has been decided to continue to measure the filtrate flow. Each 8,000 m^3/h (more or less each 32 hours) the filters goes to backwash. The backwash is done with water and air flow, first with water and air and then only water. The following table gives an indication of the water and air flows during the two phases.

Table 4.3: Water and air flows and their duration during the backwash of the limestone and the rapid sand filters.

	Q water [m3/h]	Q air [m3/h]	Time [s]
1st phase	600	900	750
2nd phase	300	-	870

Costs

The construction costs are the costs for the storage tank and the reservoir of raw water and an extra pump to bring the water from limestone filtration to the rapid sand filtration.
The management costs are to give to the pumps an higher hydraulic head, to buy and transport the Juraperles grains.

Results

The iron removal can be almost complete, so that the final concentration can be almost zero.

The other advantage of using limestone filtration is an increase in the hardness of the water and an increase in the buffer capacity. The last rapid sand filters are used to capture the last iron hydroxide flocks and to improve the suspended solid removal (the grains diameter is lower than the one used in the actual rapid sand filtration).

4.3 Improving the cascades

As it was already mentioned, the cascades are not an efficient aeration system, in fact it is possible to remove only the 10-20% of the CO_2 for each step, this means that with six steps the achievable efficiency could be 47-74%.
Therefore if we want to improve the aeration system without eliminating the existing structure we could increase the number of steps of the cascades.

The advantages of this solution are:
- The existing cascades are maintained
- The cascades are a system not sensitive to clogging and to iron settling
- The cascades are not much sensitive to possible changing in the hydraulic load

But it is necessary to consider some great disadvantages:
- Adding some steps the ceiling of the building have to be raised
- The pumps have to be changed because more energy is needed to reach the last step of the cascades

Calculation of the number of steps needed:
The measured CO_2 concentration in the water already treated by the cascades is 5,5 mg/l. Assuming that the cascade efficiency is in total about 68%, that means 15% for each step, it is possible to calculate the initial concentration of CO_2 :

5,5 mg/l : 8,5 mg/l = 68 : 100

Knowing the pH of the water and CO_2 and HCO_3 concentration after the cascades we can calculate how much CO_2 it is necessary to remove in total in order to achieve a pH of 8, that is the required pH to obtain satisfying results in iron removal:

Tab 4.4: Values before and after the cascades

N° of step	CO_2 removed
1	15,00
2	27,75
3	38,59
4	47,80
5	55,63
6	62,29
7	67,94
8	72,76
9	76,85
10	80,33
11	83,28
12	85,79

Considering that, to achieve a pH of 8, the ratio between the carbon dioxyde and the biocarbonate is

1 : 50 = $[CO_2]$: $[HCO_3]$

the CO_2 concentration which it is necessary to reach is 0,0268 mmol/l, that is 1,18 mg/l. Therefore the required efficiency is:

(Cin – C out)*100/ Cin = (8,1 – 1,18)*100/8,1 = 85%

As we assumed before, the efficiency of each step of the cascades is about 15%. In the next tab it is quoted the percentage of CO_2 removed after each step

Tab 4.5: Steps necessary to achieve a CO_2 removal of 85%.

	CO_2		HCO_3		pH
	mg/l	mmol/l	mg/l	mmol/l	
Before cascades	8,1	0,184	88	1,44	7,47
After cascades	5,5	0,125	81,74	1,34	7,47

Besides that, we have to consider that in the hydraulic scheme the first step of the cascades should be now 1,3 m higher, hence it is necessary to increase the power of the pumps to fill this gap.

We can conclude that the number of steps to have an efficiency of the 85% is 12. Therefore it is not convenient and anyway not possible at all to realize this solution because of the great number of steps, we would have to rebuilt almost the whole structure.

4.4 Changing the aeration system

If we decide to change the first aeration system, the cascades will be replaced and the second aeration system will not be necessary anymore.
In theory there are several possibilities which could be applied in this case:

- Spray aerator
- Bubble aeration
- Tower aerator

In the **spray aerator** the water is divided into very small droplets or a thin film which results in a large air-water interface. Upwards and downwards spraying are available, but in this situation it should be more convenient the second possibility applied directly above the sand filter. Despite this, we can highlight at least two important disadvantages in the use of this system: the sensitivity to clogging and the fact that the removal efficiency of CO_2 is not enough (40-50%).

As regards the **bubble aerator**, it consists of open tanks in which the air in pressure is blown through holed tubes, plates of porous materials, candles etc.
A great advantage of this system is that it takes a smaller space than the spray aerators (even if it is still bigger than the gravity aerators), but it also has the disadvantage of having a high contact time.
Among the various kinds of bubble aerator, the one which would suit the most the structure of the plant is the plate aerator (Fig. 4.3 and 4.4). This system is usually formed by a tower where the water flows over the plates creating a bubble bed of water and air. Its most important advantage is the high ratio Area/Volume which allows a big gas transfer. Unfortunately there are also numerous disadvantages, first of all the sensitivity to clogging due to the small orifices present in the plates and then some short-circuits can occur influencing negatively the gas transfer.
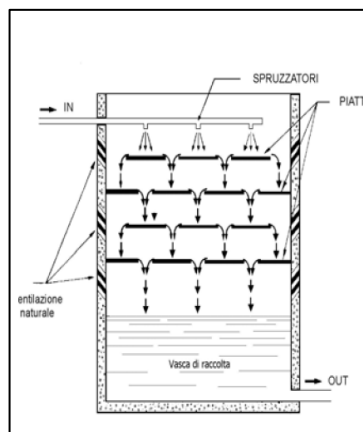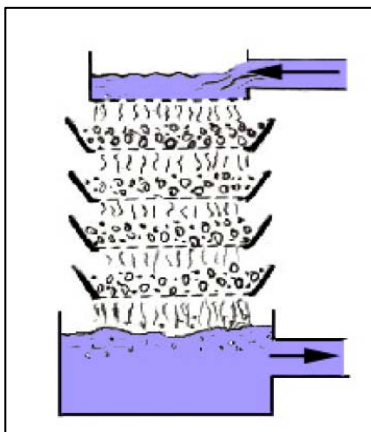
Figures 4.3- 4.4: Examples of plate aerators

Despite all of this systems have their advantages, the most convenient solution seems to be using the **tower aeration**. In fact it has a very large contact surface due to the packing material that fills the tower and therefore it has a really high efficiency which can reach also the 95%; it can be sensitive to clogging but it is relatively easy to clean it with a backwash flux and finally it already exists in the treatment scheme.
If this solution is chosen we have first to verify the treatment capacity of the towers.

In Harderbroek plant there are three towers and the maximum flow that can go through is 320 m^3/h. The plant has been designed for a maximum flow of 1800 m^3/h, therefore it would be necessary to add three more towers.

The towers cause a bigger energy loss than the cascades, this means that the pumps have to be more powerful. The gap of energy that they have to fill taking the water from underground to this first treatment is about 2 m higher. Beside this fact, it is necessary also to add another group of pumps after the filtration to allow the water to reach the clear water reservoir, in fact it is not possible anymore to reach it just thanks to the gravity force.

Treatment scheme 1

One problem to solve is where to locate the three more tower that have to be installed. A solution could be positioning them in the place where the cascades are now. Therefore it should be necessary to demolish them in order to create a space for the towers. The water pumped from the reservoirs should be sent first to this tower and if the demand (and hence the discharge) increases the other three towers have to be switched on.
Another transformation that has to be taken into account is the change which occurs in the pipes and pumping system. In fact the water will from the towers to the filters, and then the water is going to the clear water reservoirs.

Adopting this solution two lines are still maintained as we can conclude from the previous description, the first line consists of the three towers in the place of the cascades and the second one consists of the old three towers.

Cost

The calculation of the costs has to be considered:
- The construction of new pipes and demolition of some of the existent ones
- The purchase of three more tower aerators
- More energy consumption
- Substitution of the initial pumps

Considering that all this factors influence the costs, it is possible to think to another more logic and less expensive solution.

Treatment scheme 2

This one maintains both cascades and tower aerators (Figure 4.5). The towers are the first step, then the water is pumped to the cascades and finally to the sand filters. In this case it is not necessary to purchase new towers because the existing ones can provide to treat the medium flux and during the peaks the water can be directly shifted to the cascades.
Not many changes occur in the hydraulic line scheme: the increase of the power of the pump which takes the water to the towers, the addition of a pump which carries the water from the towers to the first step of the cascades, while the pumps that were used to transport the water from the filters to the towers can now be used to carry the water to the reservoirs.
Besides this it is necessary to consider also some changes in the pipes inside the plant because of the different sequence of the treatment and because of the eventual by-pass in case of peaks (as previously stated the surplus of water can flow directly to the cascades).
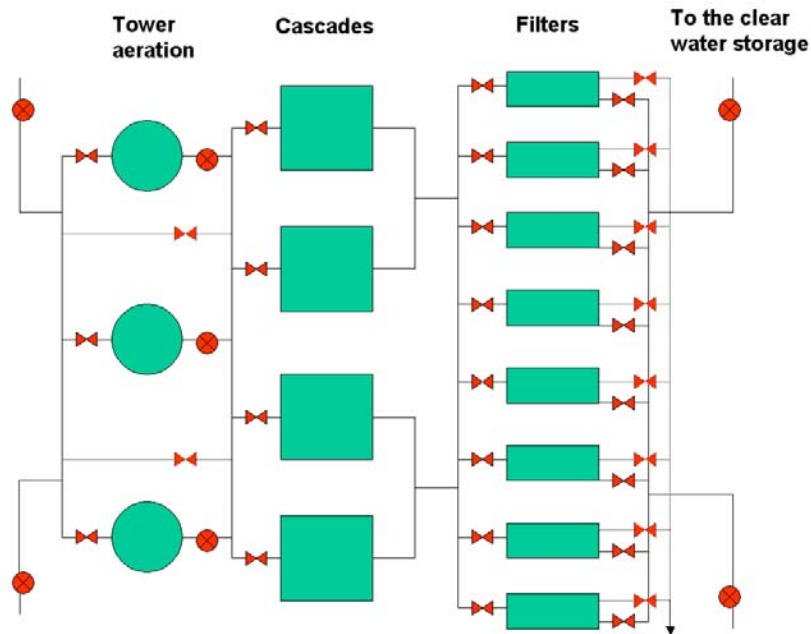
Figure 4.5: Process scheme of the alternative 4.4, Treatment scheme 2.

For both cases (Treatment 1 and 2) it is necessary to calculate the flux of air that has to go through the towers:

Assuming an infinite contact time for the reaction, the efficiency (K) of the system is expressed by the following formula

$$K = (1+ k_d/RQ)^{-1} \qquad\qquad (7)$$

Where k_d is 1,23 for the CO_2 and RQ is the ration between the discharge of air entering the tower and the discharge of water treated in it.
We know that with a tower aeration it is possible to achieve an efficiency of the 95%.
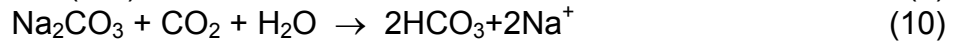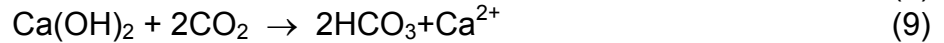
$0,95 = (1 + 1,23/RQ)^{-1}$

RQ = 23,4

This means that with a flow of 320 m^3/h a discharge of about 7500 m^3/h is required.

4.5 Adding of chemicals

A reliable method to increase the pH of the water is dosing a chemical substance. This could be sodium hydroxide (NaOH), lime (Ca(OH)$_2$) or sodium carbonate (Na$_2$CO$_3$).
The result of introducing these reagents is to remove the CO_2 by converting it into bicarbonate, the process is explained by the reactions 8, 9 and 10.

$$NaOH + CO_2 \rightarrow HCO_3 + Na^+ \tag{8}$$
$$Ca(OH)_2 + 2CO_2 \rightarrow 2HCO_3 + Ca^{2+} \tag{9}$$
$$Na_2CO_3 + CO_2 + H_2O \rightarrow 2HCO_3 + 2Na^+ \tag{10}$$

The dosage of one of these chemicals should be positioned after the cascades and before the rapid sand filters.

It is possible now to calculate the amount of each of these chemicals that is necessary to reach the required pH.

Tab 4.6: Values before and after the adding of chemicals.

	CO_2		pH
	mg/l	mmol/l	
Before chemicals	5,5	0,125	7,47
After chemicals	1,18	0,0268	8

The values quoted in tab 4.6 result from what has been explained in the paragraph 3.3.

Therefore it follows that we have to remove:

0,125 – 0,0268 = 0,0982 mmol/l   of CO_2

this means that, to achieve a pH of 8, it is necessary to add:

NaOH = 0,0982 mmol/l = 3,928 mg/l
$Ca(OH)_2$ = 0,0491 mmol/l = 3,633 mg/l
Na_2CO_3 = 0,0982 mmol/l = 10,409 mg/l

Considering that the plant can treat a maximum flow of 1800 m^3/h, it must be available the following quantity for each of the chemicals:

NaOH = 7,1 kg/h = 170 kg/d
$Ca(OH)_2$ = 6,5 kg/h = 157 kg/d
Na_2CO_3 = 18,7 kg/h = 450 kg/d

On the basis of this calculation we should be able to choose the right pump and the stock vessel, which are the only changes that the plant needs to realize this solution.

The volume of the stock vessel depends on the form in which the substance is purchased and on its specific weight. Knowing this king of information we can assume a storage of 3 days with the maximum flux.

This alternative seems to be very reliable and robust, but there are also some disadvantages. First of all it is necessary to pay attention to the by-products which need a disposal system to be built. Besides this more research should carried on about the iron (III) hydroxide flocks. In fact, due to the high pH, the iron (III) hydroxide flocks are often too small and the filtration system does not manage to remove them.

At last adding of chemicals is preferably avoided because of the impact on the environment, the need of building a safe storage system and the problem of by-products which are not easy to eliminate.

6. Conclusion

By the analysis of these alternatives it is possible to conclude that all this solutions are quite reasonable apart from the 1st and the 3rd. In fact the 1st gives an excellent water quality but it is not possible to afford its costs and the 3rd is not even realistic.

The other possibilities can be taken into account, in fact each of them can be introduced in the plant without relevant problems and furthermore their costs are comparable.

The alternative that we decided to choose is using the limestone filtration in half of the existing filters. In fact the adding of chemicals have been excluded because it is difficult to deal with byproducts, but in the case of limestone filtration the added chemical ($CaCO_3$) will not settle but they will enrich the hardness and the buffer capacity of the water which is considered a great advantage because the water is soft and aggressive. Furthermore this alternative has been preferred to the change of the aeration system because it is more reliable, it requires less use of energy and less changes in the plant.
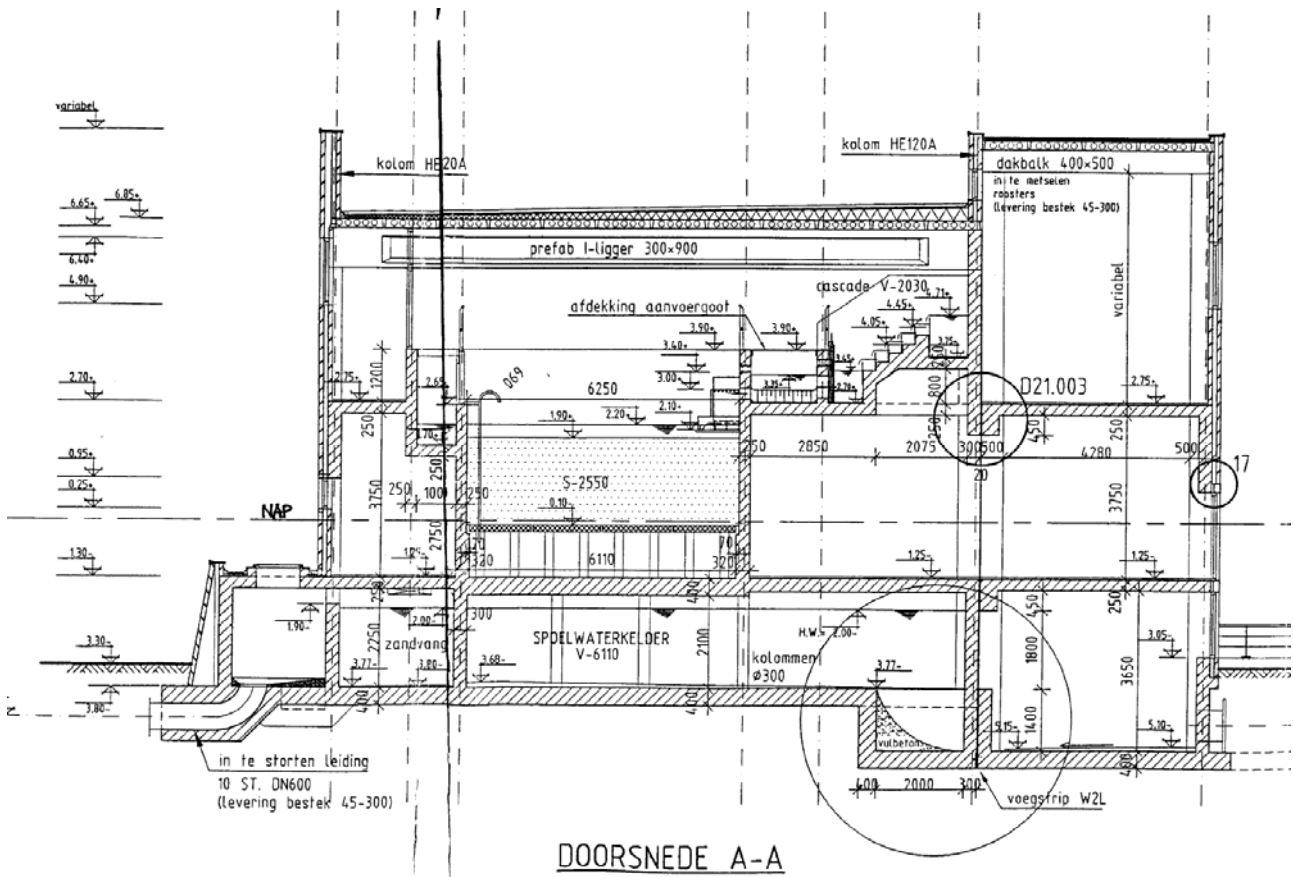
Appendix

Hydraulic scheme of the plant of Harderbroek without any change:
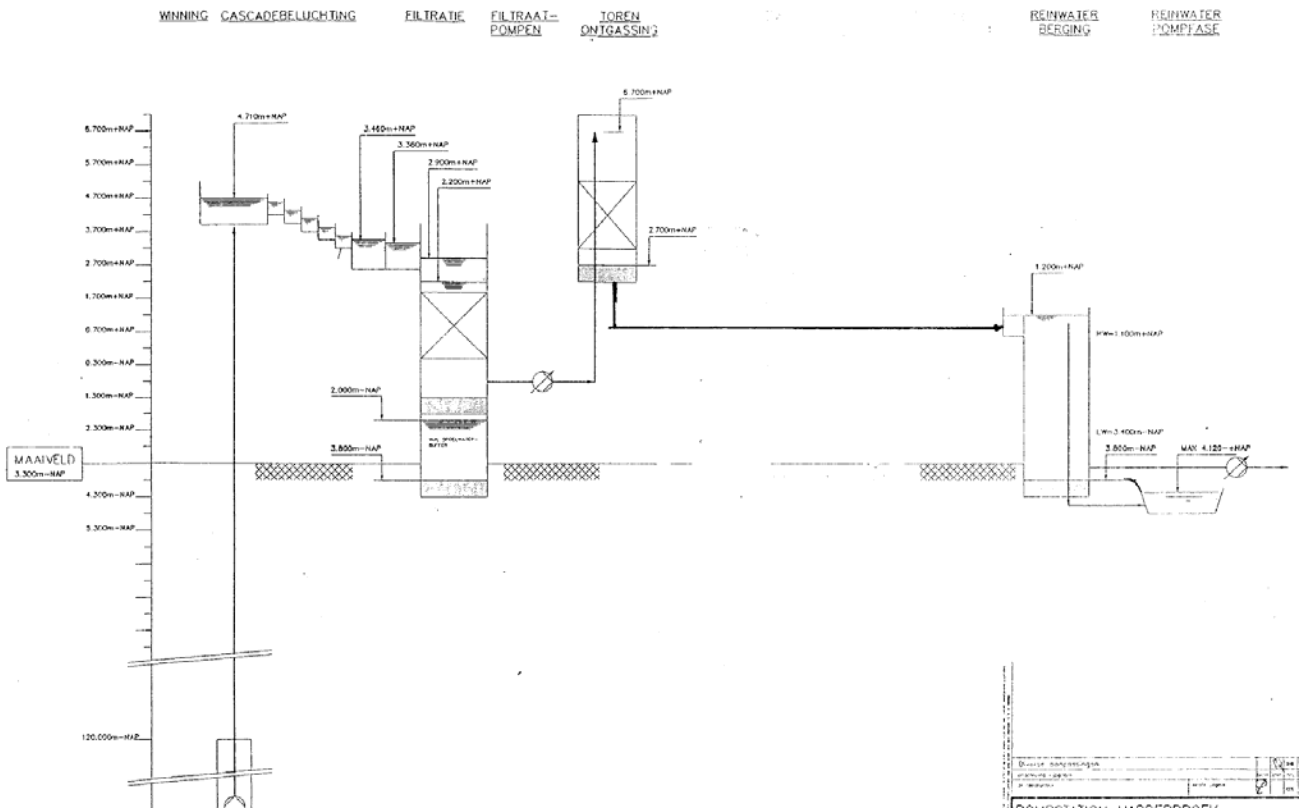
Cross section of the plant:

DOORSNEDE A-A

Hydraulic scheme of the plant for the 4th alternative (tower aeration, cascades, rapid sand filter):