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Deltares

Vitens

Universiteit Utrecht

FLEXIBILITY INCREASING SOLUTIONS FOR GROUNDWATER EXTRACTIONS

A FIRST EXPLORATION FOR SOLUTIONS

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ABSTRACT

The changing climate and socioeconomic growth form a threat for the groundwater extraction used for drinking water production in the Netherlands. Periods of severe drought result in quantitative shortages and the increasing human population and increasing surface activities result in a higher drinking water demand, while this also reduces the quality of groundwater. In order to solve this increasing quantitative and qualitative problems for the future, flexibility increasing solutions need to be implemented at the extraction location of the Dutch drinking water production company Vitens. These solutions can aim on increasing the flexibility of the amount of extractable groundwater or result in an increasing flexibility within groundwater quality. In order to be able to describe different solutions, inspiration was gained in 13 interviews with hydrological experts and three inspiration presentations from other knowledge domains. This resulted in multiple concepts that are developed into flexibility increasing solutions using available literature on *Google Scholar*. These solutions were implemented at two existing extraction locations of Vitens (Manderveen and Vechterweerd) which represent the two archetypes that are of interest (shallow groundwater extraction in a rural environment and riverbank filtration extraction). This implementation is done, to be able to give a quantitative expression of the performance of a solution and its costs. Solutions that fall within the scope of this research are selected using four criteria and after that classified in different classes. These classes are: quantity or quality solutions, internal or external solutions and a final classification is done on the expected future problems (scenario's for climate change and socioeconomic growth) that individual solution aim to solve. This classification is done, to be able to make a start in developing a toolbox for Vitens in which solutions can be implemented after observing a specific quantity or quality problem at an extraction location of the previously described archetypes. The internal and external class is used to clarify if Vitens is able to implement a solution internally, or if external stakeholders need to be drawn into the implementation process of a solution. After this selection and classification, the different solutions are tested on efficiency by dividing their yearly operations expenses by their yearly performances (€/m^3). These efficiencies are ranked in order to draw conclusions on which solution is most and least efficient. These results consist of 12 solutions that form a first investigation of possible solutions for increasing flexibility. The quantitative results of nine solutions can be used as a first rough estimate on performances and costs and to evaluate if this method works for testing the efficiency of the solutions. The results from this thesis research conclude that the external quantity solution of injection of surface water in Natura2000 areas is the most efficient solution for increasing flexibility in groundwater quantity, because it costs 0,01 €/m^3 of extra available groundwater. In this method risks are described, but not quantified, due to the unavailability of data. Besides that, the total amount of capital expenditures required for most of the solutions for the total scope of this research (100 years) is also lacking. The inclusion of these risks and costs are a relatively easy win when improving this method of testing efficiency. Besides these two possible improvements to calculate efficiencies more precisely, this method of diving total costs by the total performance of a solution is strongly recommended, because it allows for a comparison of solutions that act on different scales (regional and national).

1 INTRODUCTION

1.1 PROBLEM DESCRIPTION

Worldwide, there is a specific demand for good quality groundwater for drinking water production purposes. It is expected that sources of groundwater will become more important in the future for dealing with climate change and desiccation (Dragoni & Sukhija, 2008) (van Engelenburg *et al.*, 2018). It is therefore of great importance that water in the subsurface is managed. In the Netherlands this is becoming of greater importance every year.

One of the main concerns regarding groundwater quality in the Netherlands is the socio-economic growth. This is the result of an increasing human population and increasing anthropogenic activities on the earth´s surface. Examples of these activities are: agriculture, industry, dumps, highways, geothermal energy sources and expanding cities (Burke *et al.*, 1999). Since space in the Netherlands is limited, these activities might become a threat to groundwater bodies, because aquifers are recharged with water that has a larger risk of contamination caused by anthropogenic activities. A higher amount of contamination with pesticides, herbicides and other unwanted substances is already observed in groundwater bodies and is expected to even further increase in the future. This was identified by Vitens and Deltares and later reported (van den Meiracker *et al.*, 2020).

To add on this, climate change increases the rate of groundwater contamination caused by surface activities (MacDonald *et al.*, 2003). Nowadays we already notice an increasing amount of more dry periods in the Netherlands. It is predicted that these periods are going to be more severe, longer and are going to happen more often in the future in the eastern parts of the Netherlands (the area of interest for this study) (Philip *et al.*, 2020) (Stańczuk-Gałwiaczek *et al.*, 2018). It is hypothesized that rainfall events that occur will be more extreme and of a shorter duration, which increases the amount of runoff which relatively lowers the amount of rainfall that can infiltrate and result in groundwater recharge (Philip *et al.*, 2020). Drier periods in combination with possible higher drinking water demands (due to socio-economic growth and a possible increase in population) require periods in which more groundwater has to be extracted from the subsurface. Higher extraction rates can result in a shorter travel time of water in the water-bearing aquifers towards the extraction well. Longer travel times are favourable, because natural filtration and breakdown of contaminants occurs in the subsurface, improving the groundwater quality (Welkers, 2017). Therefore, an increase in demand causes quality to decrease (MacDonald *et al.*, 2003). This becomes an even higher risk when surface activities are becoming more common in the future affecting the groundwater protection zones. Surface activities like roads, housing or business parks can result in contamination of the protection zones, when they are located in, or close to these zones. In this way, socio-economic growth forms a thread for groundwater quality.

Groundwater quantities are the second main concern for the future. When higher extraction rates are realised at groundwater sources, it has negative results on activities on the surface: nature reserves, agriculture or wooden foundations of monumental buildings (Hellegers *et al.*, 2001). Lower groundwater levels cause desiccation of agricultural crops and nature vegetation (van den Meiracker *et al.*, 2020) and rotting foundations. This results in yield losses, biodiversity loss and collapsing buildings. A cause for these problems is a lower amount of groundwater recharge due to increased runoff and droughts (Dunkerley, 2012).

With this in mind it can be said that the supply of enough drinking water of a good quality is not guaranteed in the future in the Netherlands. The future changes in socio-economics and the changing climate ask for more flexibility in groundwater extraction for drinking water production purposes.

1.2 PLACE WITHIN THE BIGGER PROJECT “FLEXIBLE GROUNDWATER EXTRACTION”

The above described foreseen problems with supplying enough drinking water of good quality led to the project “Flexible Groundwater Extraction”. This project is a cooperation of the Dutch drinking water company Vitens and the institute for applied research Deltares. The goal for these two parties is to secure the drinking water supply for the customers of Vitens in the five Dutch provinces where Vitens operates (Friesland, Overijssel, Flevoland, Gelderland and Utrecht (*figure 1*)) for the next 100 years (until the year 2121). The research project described in this thesis is commissioned by Vitens and Deltares and has the goal to identify solutions that can increase flexibility within groundwater extraction. Besides that, a start is made on testing these solutions on efficiency. The expected results of this thesis are a list of flexibility increasing solutions and an advise on how to test these different solutions on their individual efficiency. This information is useful for Vitens and Deltares, because they are lacking knowledge on flexibility increasing solutions and the hands on information on the testing of solutions helps them when developing their own method for testing the efficiency of solutions.

Figure 1 The Netherlands and the five provinces of Vitens (purple). Source: *Vereniging van Waterbedrijven in Nederland*.

1.3 THEORETICAL BACKGROUND OF THE “FLEXIBLE GROUNDWATER EXTRACTION” PROJECT

1.3.1 FLEXIBILITY

Vitens and Deltares defined the concept of flexibility for this project as: “*the ability of an existing extraction to adapt to a changing situation when specific shocks or disturbances occur”* (van den Meiracker *et al.*, 2020). The most important criteria for flexibility as described by Vitens (Kloosterman, 2020) are:

- Dealing with shocks produced by the environment. Resilience results in absorption of the shocks that are produced by the environment (natural and social). This absorption of external shocks results in a constant drinking water production that is satisfying the customers need. In other words: enough drinking water of a good quality when external extremes occur.
- Adaptation: being able to adapt to a changing environment. An example in the scope of the “Flexible Groundwater Extraction” project is the ability to increase or decrease the extraction rate of groundwater at a specific location if needed.
- Speed. A faster adaptability to changes in the environment result in a higher flexibility.

1.3.2 STORYLINES

To explain what the previously mentioned shocks are, Deltares and Vitens developed different storylines (*figure 2*) to explain the possible variety in drinking water demand in the future (van den Meiracker *et al.*, 2020). These are arranged below by an increasing need for flexibility. In other words: the first storyline requires least flexibility and the fourth requires the most flexibility. These demand curves are related to climate change and socioeconomic changes.

1. **Little variation with high predictability**. Changes that occur in this scenario are predictable and very gradual. Little flexibility is required because there is enough time to respond to changes via regular paths. The increase in demand might be so gradual that new extraction locations can be developed before an expected demand is reached (development of a new location usually takes 15 years) (Kloosterman, 2020). This means that flexibility in this scenario is of minor importance.
2. **Predictable but significant variation**. In this scenario, the demand differs greatly, but in a predictable rythm. It is expected to be a daily or seasonal scale. The amount of flexibility needed here is known, since the fluctuations in demand are highly predictable over time and in magnitude.
3. **Unpredictable, large scale event change**. This scenario includes unpredictable disasters that are very rare but require an urgent solution. A high level of flexibility is needed at unpredictable events such as tsunamis, cyber attacks, pandemics, terrorist attacks or sudden immigration of large groups of people.
4. **Unpredictable with a significant variation**. High fluctuations on an unpredictable scale are visible in this scenario. A complex and non-constant pattern can be developed by multiple different new activities, for example: consumers start to produce their own drinking water, unexpected pollution events or sudden migration.

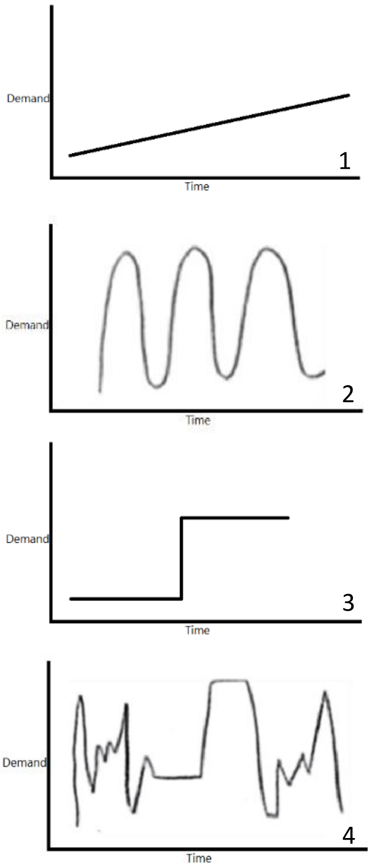

Figure 2 Schematic representation of the demand versus time of the different storylines as expected by Vitens and Deltares (van den Meiracker *et al.*, 2020).

1.3.3 ARCHETYPES

From these storylines it becomes clear, that solutions need to be found to increase flexibility for groundwater extraction locations to meet future water demands. To be able to give specific solutions to enhance flexibility, the way of groundwater extractions used by Vitens needs to be introduced. Vitens and Deltares defined six different archetypes to extract water for drinking water production of which four archetypes are based on existing Vitens extraction types. Together with Vitens and Deltares, it has been decided to investigate only two of these archetypes in more detail due to the limited time for this internship and the expected large variation in solutions for these two archetypes. These archetypes including their main problems are described and displayed (*figure 3*) on the next page.

ARCHETYPE A) SHALLOW GROUNDWATER EXTRACTION IN A RURAL ENVIRONMENT

This archetype is relatively vulnerable to droughts, because the shallow aquifer is in direct contact with the surface where extraction rates are increased during droughts and the recharge is zero during droughts. Specific extraction rates caused by peak demands have devastating results for nature reserves and agriculture above the aquifer, these might experience serious drought damages (van den Meiracker *et al.*, 2020).

With respect to groundwater quality, travel times of the groundwater are relatively short. Which results is a major threat for the quality of the extracted groundwater due to the short distance between sources of contaminants and the extraction well. Besides that, the retention time of the water below the surface is relatively short which only gives it limited time to be filtered by natural processes in the subsurface (van den Meiracker *et al.*, 2020).

ARCHETYPE B) RIVERBANK-FILTRATION EXTRACTION

The main quantity issue for this archetype is a low water level within the river that is used as a source of water. It has to be mentioned as well that water extracted in this archetype is often not fully originating from a river source. Part of the extracted water is groundwater that has a similar source as the archetype described above. Quantity issues from that archetype need to be considered for this archetype as well (van Vught *et al.*, 2017b). In the case of water quality: the groundwater that is extracted in this second archetype risks contamination from substances that are supplied by rivers. It is hard to control the quality of river water due to the rivers length and pollution processes taking place in upstream regions or even countries. This requires communication and policymaking between many parties (Munia *et al.*, 2016). One of the most important sources of upstream contamination are from sewage Waste Water Treatment Plants (WWTPs) (van den Meiracker *et al.*, 2020). This in combination with relatively short travel times from the river towards the extraction location results in a risk for contamination of extracted groundwater

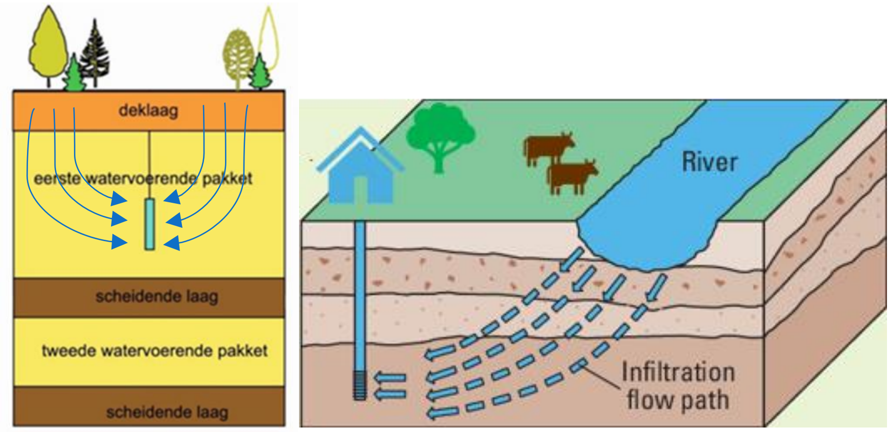

Figure 3 Schematic representation of the two archetypes that are investigated in this study. Left is the shallow groundwater extraction in a rural environment and right is the riverbank-filtration extraction (van den Meiracker *et al.*, 2020).

1.4 THESIS RESEARCH PROJECT

1.4.1 KNOWLEDGE GAPS AND AIM

Three knowledge gaps are distinguished by Vitens and Deltares within the bigger project "*Flexible Groundwater Extraction*". There is a lack of knowledge on:

1. Internal solutions on how to increase flexibility within the drinking water production systems. Internal solutions are defined as solutions that can be implemented by Vitens in and around an extraction well.
2. External solutions on how to increase flexibility within the drinking water production systems. Extern solutions can often only been implemented by other stakeholders in the drinking water production process and are therefore beyond the reach of Vitens. Stakeholders can be farmers, nature organisations or regional water authorities. External solutions are often social, when different parties can help each other in reaching their individual goal.
3. How efficient these newly found internal and external solutions are and how to test this efficiency.

The aim of this thesis is to fill these 3 knowledge gaps for the two previously described archetypes.

1.4.2 RESEARCH QUESTION

These recognized knowledge gaps, aim and archetypes for this internship study can be summarized in the following main research question:

What flexible groundwater extraction solutions are most efficient when coping with expected future shocks at the shallow rural- and riverbank-filtration extraction locations of Vitens?

Three sub questions are positioned in a specific order to narrow down towards an answer to the main research question. These are:

1. What internal solutions can be implemented at two existing wellfields in order to make them more flexible? (to find solutions that can be implemented in two real-world examples to fill knowledge gap 1)
2. What are external solutions that can increase flexibility within wellfields of the described archetypes? (filling knowledge gap 2)
3. What is the efficiency of these solutions from sub question 1 and sub question 2 and how useful is the method used to quantitatively express this efficiency? (filling knowledge gap 3)

These sub questions are answered using case studies in three different steps, which are explained in the next chapter.

2 METHODS

2.1 CASE STUDY AREAS

The three previously called sub questions are answered using two case studies of two existing extraction locations of Vitens (Manderveen and Vechterweerd). These locations are currently experiencing problems that are common problems in the two archetypes they represent. Case studies are chosen to be able to work with real problems and real data instead of schematic and conceptual models. These locations have been selected by the intern in consultation with Vitens based on the degree of flexibility that is observed at these locations nowadays. At both locations Vitens wants to increase the degree of flexibility. Besides that, these locations are perfect examples of the archetypes that are of interest.

1.5.1 SHALLOW GROUNDWATER EXTRACTION IN A RURAL ENVIRONMENT - MANDERVEEN

Manderveen is located in the east of the Netherlands at the Dutch-German border. This extraction location consisted of two well fields: Manderveen and Manderheide. The nature around this second well field appeared to be very vulnerable to groundwater extraction. For this reason, Manderheide was closed in the year 2008. Besides that, the province of Overijssel issued a permit for the original Manderveen location until the year 2023 with a size of 3 million m^3/year. When no alternative location can be found in this region, the Manderveen location can still be used after 2023, but with severe limitations for its extraction rate.

To protect the quality of the extracted water, different zones around the extraction location are developed (van Vught *et al.*, 2017a). These three zones and their characteristics are visible in *table 1*:

Table 1 Protection zones around groundwater extraction locations of Vitens. *21% of the "100 year recharge zone" is a natural area of Natura2000- and TOP-areas called *Springdal* and *Dal van de Mosbeek*. This land use increases the quality of the groundwater but these nature reserves are vulnerable to desiccation when extraction rates are too high.

Zone	Minimum travel time to the extraction well
Water extraction zone	60 days
Groundwater protection zone	25 years
100 year recharge zone*	100 years

The extraction location at Manderveen is located in the so called: *Slenk van Reutum*. This is a tectonic valley that has been descended between two fractures (*figure 4*). This valley is filled with fluvial sediments (sandy) that form the second aquifer (2) (*Urk, Peize* and *Oosterhout formations*). At the sides and the bottom it is protected with clay layers which have a low permeability (*Breda formation*). The top of the aquifers is protected by other sandy clay layers (*Drenthe formation*). Above these sandy clay layers a layer of sand (*Boxtel formation*) can be found which is the first aquifer (1).

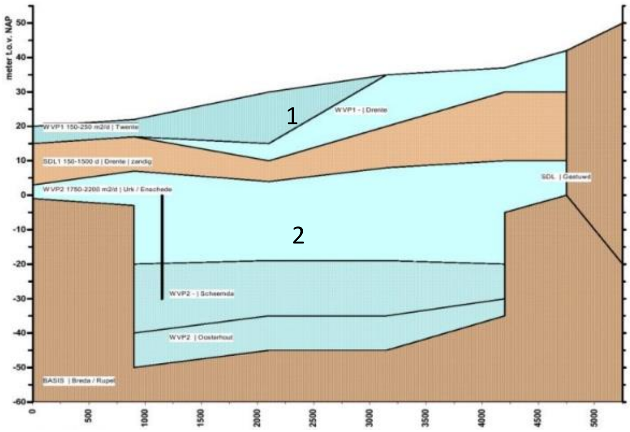

Figure 4 Geohydrological situation at the Manderveen extraction (van Vught *et al.,* 2017a). 1 is the first water bearing aquifer and 2 is the second water bearing aquifer from which Vitens is extracting.

Despite the previously called protection areas and partly protecting clay layers, contamination of the extracted groundwater is observed. Problematic substances in this location are mostly from an agricultural source. This nitrate is present close to the signal value of 50 mg/l (EU Directive 2006/118/EG)). Other important contaminants are heavy metals that are all present above their individual signal value (iron > 200 µg/l, aluminium > 0.2 mg/l and nickel > 20 µg/L). Contaminations can relatively easily reach the aquifer because fully confining layers are lacking. Besides these qualitative problems, there is a limitation on the extraction rate due to the threat of desiccation of the Natura2000 areas and ditches for agricultural purposes that are located in the area above the Manderveen extraction (van Vught *et al.*, 2017a).

1.5.2 RIVERBANK FILTRATION EXTRACTION - VECHTERWEERD

The extraction location of Vechterweerd is also located in the province of Overijssel, next to the river Vecht. This riverbank-filtration extraction has a permit to produce 8 million m^3/year, but the current goal is to produce 2 million m^3/year in order to monitor the consequences of groundwater extraction in this area. Just as the Manderveen location, Vechterweerd has an water extraction zone, groundwater protection zone and 100 year recharge zone.

The top of the aquifer from which groundwater is extracted is located 5 meters below the surface and continues to a depth of around 40 meters below the surface (1) (*figure 5*). This coarse sand is highly permeable due to the presence of fluvial sediments from the *Kreftenheye formation*. Above this *Kreftenheye formation* are no confining layers located. At 10 meters below the surface, a thin clay layers can be found from the *Eem formation*. This layers is partly protecting a part of the aquifer below this clay layer. It has therefore been decided to extract water from this deeper part of the aquifer, below this *Eem formation* (at -16 to -37 m). Travel times in this aquifer are relatively short (between 1 and 100 years). Besides this *Eem formation*, there is no protection against infiltration of contaminants by a confining layer

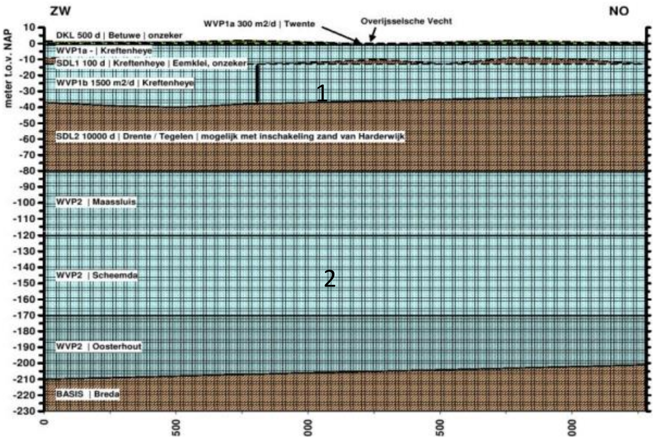

Figure 5 Geohydrological situation at the Vechterweerd extraction location (van Vught *et al.*, 2017b). 1 is the first water bearing aquifer from which Vitens is extracting and 2 is the second water bearing aquifer.

Below the *Kreftenheye* formation a thick clay layer is deposited called *Tegelenklei*. This clay layer is highly impermeable and therefore protects the deeper aquifer (2) that is located below this *Tegelenklei*. This second aquifer consists of coarser sediments from the *Maassluis*, *Scheemda* and *Oosterhout* formations. The base of this aquifer is located at 210 meters below the surface. Nowadays there is no groundwater extraction from this aquifer.

The biggest part of the extracted water at Vechterweerd comes from the river Vecht itself (45%) another part comes from other surface waters, which are often also fed by the river Vecht (15%) and the other 40% is groundwater from surface infiltration.

The archetype and therefore the extraction location at Vechterweerd is strongly dependant for their water quantity and quality on the river Vecht. Especially the quality of the surface water of the river Vecht is influenced by the upstream activities of other regions in the catchment area of the river. This becomes extra important in periods with low river discharges (summers). This makes the concentration of contaminants relatively high, since there is less river water to dilute these contaminants. For this reason, the quality of the extracted water in summer periods is very vulnerable for event calamities (illegal discharge of drug waste or traffic disasters). This will become more of a concern in the future. Drought events are expected to happen more often, for a longer time and are expected to be more severe, lowering the discharge of the Vecht and therefore increasing the concentration of contaminants.

Besides this risk, there are already contaminants found in the extracted water with alarmingly high values. Contaminations mostly include drug residues (from sewage Waste Water Treatment Plants), pesticides and herbicides that are originating from the river Vecht. These contaminants are all present above the common signal value of 0.1 µg/l (EU Directive 2006/118/EG). This is alarming and asks for additional steps during the filtration of the extracted water.

2.2 GENERAL APPROACH

The main research question will be answered by stepwise answering the three sub questions (SQ1, SQ2 and SQ3). These different steps are visible in *figure 6*. In step 1 possible solutions to increase wellfield flexibility are selected using several criteria. Step 2 includes classification of the previously found solutions. Classification is necessary to distinguish between internal and external solutions and the different storylines that are aimed to be improved. Finally, in step 3 the selected and classified solutions are tested on and ranked according to their efficiency. In *figure 6* the sub questions are linked to the different steps from the general approach and the knowledge gaps (k. gap) that are aimed to be filled.

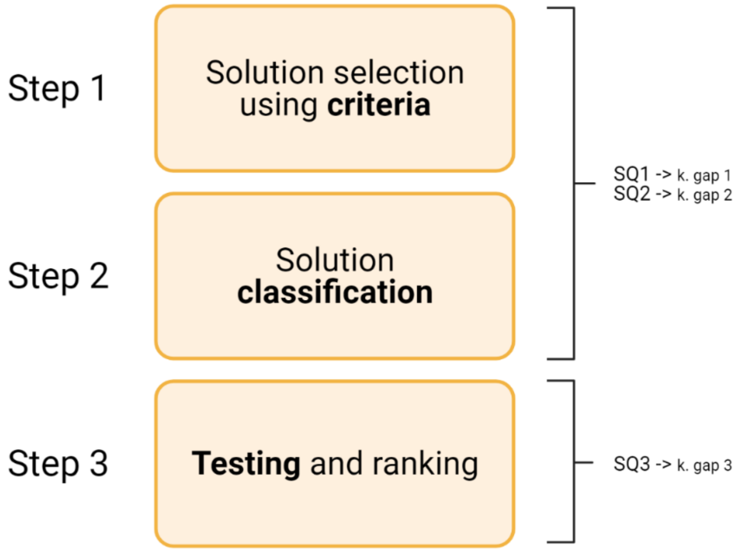

Figure 6 General approach: solution selection, classification and ranking.

2.3 STEP 1: SOLUTION SELECTION

In this first step, the first and second research question and knowledge gaps 1 and 2 are covered. Solutions need to be found or developed to solve the problems of the case study areas described above. This is done using the following method:

The problems that may arise in the future for these two locations will be tackled with the concept of backcasting (Robinson *et al.*, 2011). In this article the authors explain how a desired future can be achieved by looking at desired future scenarios and developing solutions to get that desired future scenario. The future scenario's that are expected are already described above and need to be adjusted to the desired future scenario's in which external shocks are absorbed and no shocks are produced to the customers of Vitens and the environment. To get these desired future scenario's, solutions into the drinking water production system are required that increase the flexibility of the process. These solutions are part of the results for the first and second research question. Answers to these research questions have been found via a literature research on *Google Scholar*. Search terms are related to the future scenario's that are desired and to the classification system that will be discussed in the next paragraph.

The basis for inspiration for these solutions can be found in meetings with expert from Vitens, Deltares and Ruimtevolk. A total of 13 experts has been asked what they think are the most promising niches where flexibility can be increased in their knowledge domain. A list of the experts that contributed to this research is visible in *Appendix I*. Deltares and Vitens also organised three inspiration presentation from experts from other knowledge domains, to stimulate to be able to think outside of the box. Topics in these presentations were: flexibility in nature, language and the human brain. After being inspired by these expert meetings and inspiration presentations, a goal oriented literature study could been performed.

The selection of possible solutions for the two archetypes is schematized in step 1 of *figure 9*, which is a flow chart displaying the total process the solutions underwent in step 1 to 3. Because it was hypothesized that there were many solutions that are able to increase flexibility within groundwater extraction, criteria needed to be clear for the selection of the possible solutions in step 1 of the flow chart. The most important criteria according to Kloosterman *et al.*, (2020) are 1) no deterioration of drinking water quality and 2) no deterioration of drinking water quantity. Every solution should meet at least one of these two criteria. Other criteria include factors that are important for flexibility and are already described in chapter one, these are: 3) adaptation ability, 4) resilience and 5) speed. Since speed (faster adaptability) has a major overlap with criterion number 3 it was decided to not use this fifth criterion. For this reason every solution should meet criterion 1 or 2 and criterion 3 or 4 to be selected. After this selection to solutions that are interesting for this study, the solutions needed to be classified in step 2.

2.4 STEP 2: SOLUTION CLASSIFICATION

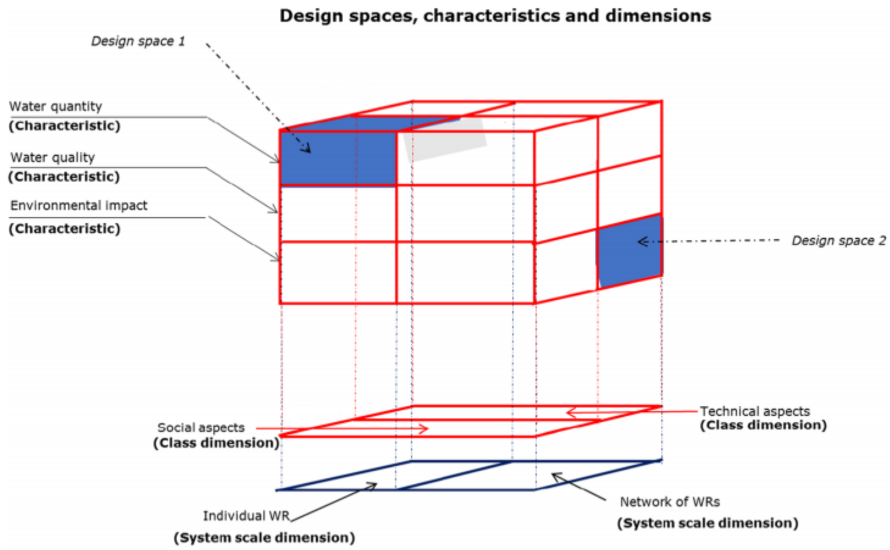

Figure 7 Water Resource Design Principles Framework (Kloosterman *et al.*, 2020).

Classification of the solutions from the previous step is done in step 2. This classification is necessary to develop a “toolbox” in which different classes of solutions are linked to the storylines that are aimed to be improved. This “toolbox” facilitates future choices between solutions when specific problems are observed. Classification is done according to a recently developed framework. This *Water Resource Design Principles Framework* (Kloosterman *et al.*, 2020) covers 3 main problems that may occur during the extraction of groundwater: poor water quality, low water quantity and the impact of groundwater extraction on the nearby environment. These 3 problems form the first dimension (y-axis) of the design framework and are visible in *figure 7*. The second-dimension (x-axis) includes social aspects and technical aspects where solution for future problems can be found. An example solution in the social aspect is possible cooperation of the staff of nature reserves in order to help Vitens to reach goals. What drives this cooperation is a common goal. A technical aspect is for example increasing the extraction rate or a filtration process. The third and last dimension (z-axis) is a scale dimension and distinguishes between an individual water resource (WR) (well field) and networks of water resources (WRs) (multiple wellfields that are extracting from the same aquifer). Solutions can be found for an individual WR, but combining the extractions in specific ways is hypothesised as an important possibility to increase flexibility (van den Meiracker *et al.*, 2020).

This framework is of great value for classifying solutions but might also cause this literature study to become too complicated and time consuming. Therefore, it had to be adjusted to make it suitable for this research. First, the environmental impact has been removed from the first dimension. Which results in the first two main classes: quality solutions and quantity solutions. Solutions to solve the environmental impact were not investigated in this thesis, since the focus is only on securing enough good quality drinking water for the customers of Vitens in the future and not on reducing the impact on the environment. The technical and social class from the original framework were renamed to internal and external solutions in order to fit to this research. This was necessary, because it became clear that most of the social solutions could only be implemented by external parties and where often also technical solution. For this reason it was decided to reduce complexity and choose for an internal and external subclass in the second dimension. These classes clearly distinguish between the first and second knowledge gap. The third dimension distinguishing between solutions for an individual WR and networks of WRs and is not used as a subclass for this thesis research. This is done, because combining multiple wellfields is a specific solutions for a specific extraction location and is therefore less relevant for an archetype in general. It is relevant to remember that solutions are aimed to be found for two archetypes in general and not especially for the two case study areas (which are only a tool to quantify different solutions). To be able to link the new solutions to different storylines they aim to improve, the previous third dimension is replaced by a new third dimension, in which storyline 1-4 each for a new subclass.

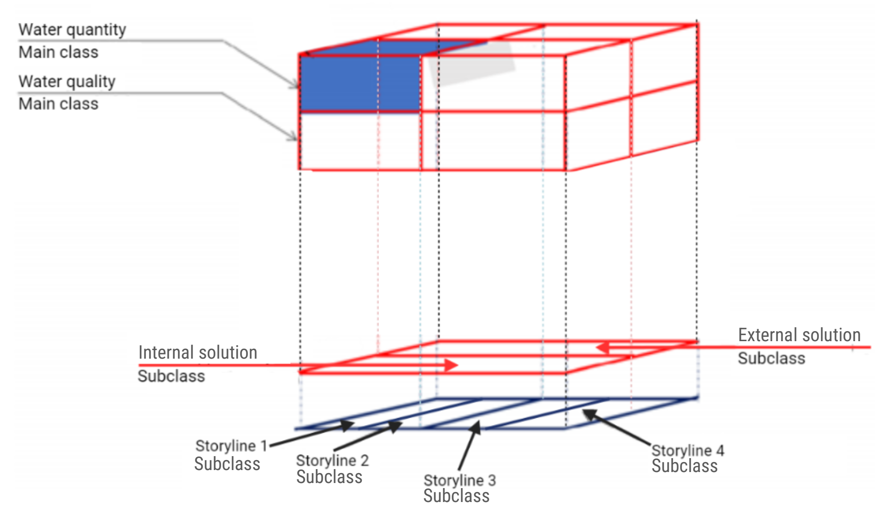

Figure 8 Customized version of the "Water Resource Design Principles Framework" suitable for this research.

The adjusted version of the *Water resource design principles framework* that suits to this study and is used for classification of the new solutions in step 2 is visible in *figure 8* and implemented in the flow chart of *figure 9.* The classification of the selected solutions will function as a toolbox in which they are sorted according to the main- and subclasses. A toolbox can be useful in the future, when specific quality or quantity problems occur, according to a storyline. This allows Vitens to implement tailor-made solutions for these problems internally or start a procedure to implement an external solution This classification toolbox is visible in *table 2* with imaginary solutions called X, Y and Z.

2.5 STEP 3: TESTING EFFICIENCY

In this final step the third sub question is answered. The solutions presented in sub question 1 and 2 are tested for their efficiency. In this research, efficiency is defined as the improvement of groundwater quality or quantity compared to their costs. A relatively high improvement with low costs, results in a high efficiency. It is hypothesized that this testing of the different solutions will be complicated, since the solutions can have a high variability when looking at the classification framework from step 2. For this reason it is decided to only try to quantitatively express two factors for each solution: performances and costs and compared these to each other in order to decide which solution is most efficient. Where necessary, data from the case study areas is used to estimate values for these two factors. Possible risks are not quantified, but will be investigated and appointed (*table 2*). For this reason efficiency will for now be tested on:

Performance is defined as the amount of improvement or no deterioration in groundwater quantity or quality after implementation of a solution, and is expressed in a number. These numbers are collected using a literature study, or calculated for the case study areas using available information. Because calculations differ per solution, relevant information and equations are explained in the results section at the corresponding solution. The units of these performances vary, since solutions can have an impact on groundwater quantity (expressed in m^3) or quality (expressed in % contaminant reduction). For this reason quantity and quality solutions were aimed to be ranked separately. Besides this, solutions can act on different scales. Internal solutions are implemented on a local scale, while external solutions can be implemented on a national scale.

The **costs** of a solution provided an opportunity for comparison of solutions that act on these different scales. These costs consist of: Capital Expenditures (CAPEX), which include costs that are only made once during the implementation of a specific solution and Operation Expenditures (OPEX), which are costs that are made more than once, for example maintenance or energy costs. This CAPEX and OPEX need to be calculated for the time scope of this research, which is 100 years. The financial information is also collected using a literature study and gave an estimation of possible costs for Vitens. The case study areas functioned as an example location, if more specific location data was required to calculate costs. Since most of the data on the CAPEX of different solutions was lacking or not available, the choice has been made to only calculate the efficiency using the performance and OPEX data.

The ranking of quantity solutions has been done by calculating the efficiency of each solution. This efficiency is a number that expresses the costs of one cubic meter of water that helps in increasing flexibility (€/m^3). This allows the comparison of solutions that work on different scales. The used equation (1) for this calculation is:

$$Efficiency\ (\frac{€}{m^3}) = \frac{Yearly\ OPEX}{Yearly\ quantity\ performance} \qquad \text{Eq. 1}$$

The eventual ranking of quantity solutions is based on this efficiency value. The solution with the lowest price for 1 cubic meter of water has the highest ranking and the solution with the highest price for 1 cubic meter has the lowest ranking. The efficiency of the quality solutions could not been calculated, since CAPEX and OPEX data for most of the solutions was lacking or not available. For this reason, these solutions are not ranked (*figure 9*).

Table 2 Classification toolbox for different flexibility improving solutions including: performance, costs, risks and missing data

Solution	Main class	Subclass	Storylines				Performance	Costs	Risks	Missing data
Name	Quality/ Quantity	Internal solution/ external solution	1	2	3	4		CAPEX (€) OPEX (€/year)		
X	Quantity	Internal solution	x	x			……… m^3 $year^{-1}$	Unknown unknown	1…….. 2……..	1…….. 2……..
Y	Quality	Internal solution			x		% contaminant reduction	…€ … € $year^{-1}$	1…….. 2……..	1…….. 2……..
Z	Quantity	External opportunity	x		x	x	……… m^3 $year^{-1}$	…€ … € $year^{-1}$	1…….. 2……..	1…….. 2……..

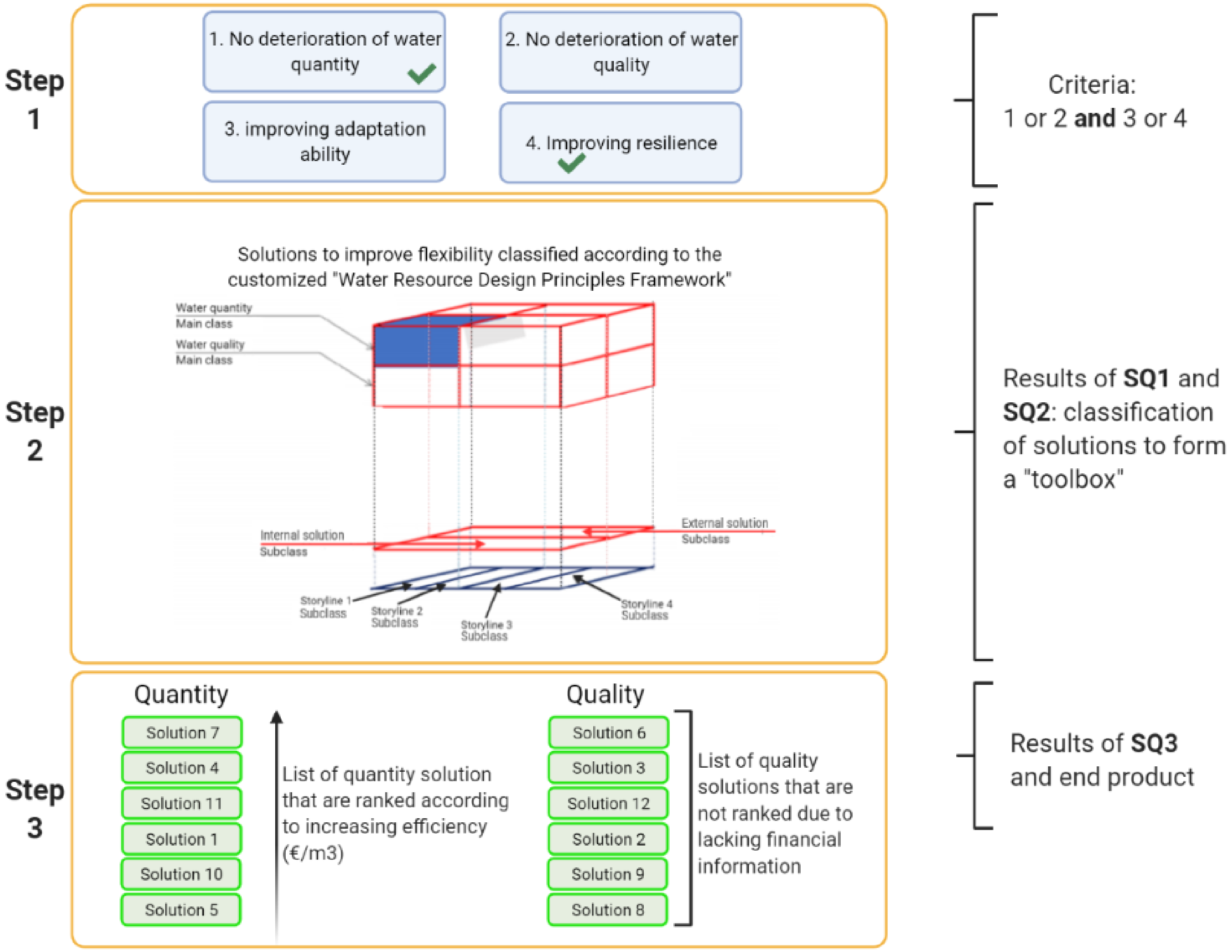

Figure 9 Flow chart displaying the selection criteria, classification scheme and eventual ranking of solutions to increase flexibility within groundwater extraction locations for drinking water production purposes.

3 RESULTS

In this section solutions are presented that are able to increase the flexibility of groundwater extraction at shallow rural extractions and riverbank filtration extractions. These solutions where selected after interviews with experts, inspiration presentations and a literature study. First, solutions are discussed that can increase flexibility at a shallow rural extraction. Secondly, solutions for the riverbank filtration archetype are discussed. And finally solutions are presented that are considered useful for both archetypes.

3.1 SHALLOW GROUNDWATER EXTRACTION IN A RURAL ENVIRONMENT

3.1.1 SURFACE WATER INJECTION IN NATURA2000 AREAS (SW N2000)

QUANTITY – EXTERNAL – STORYLINE 1, 2 AND 4

An external solution to cooperate with Natura2000 areas *Dal van de Mosbeek* and *Springendal* was observed after interviews with Stefan Jansen and Mark Niesten. This solution can result in favourable conditions for both Vitens and these Natura2000 areas. The extraction rate in the Manderveen and Manderheide extractions had to be drastically reduced in the past (from 6 Mm^3/year in 1993 to 3 Mm^3/year in 2008, together with closure of the Manderheide location) in order to protect the vulnerable Natura2000 areas from desiccation (van Vught *et al.*, 2017a). The lowering of the yearly extraction rate does not contribute to reaching the expected higher demands in drinking water. It is known that the current extraction rate at Manderveen does not affect the Natura2000 areas that are located in the eastern part of the infiltration zone of this drinking water extraction location. After closure of the Manderheide, no strong decrease in the water table can be attributed to the Manderveen extraction (maximum 5 centimetres) (Natuur en Milieu, 2019). A solutions that allows an increase in groundwater extraction can be found in injecting surface water from the *Mosbeek* (a local creek) into the soil of these Natura2000 areas. When these areas receive more water during longer periods of time, desiccation will be less likely, allowing an increase in extraction rate, which increases flexibility.

The most important area that is suffering from low groundwater tables during drier periods in the Natura2000 areas are higher elevated sandy soils (“*hogere zandgronden*”) (Natuur en Milieu, 2019). For this reason these areas are interesting when considering the injection of surface water (from another source). When this is done, the moorland habitat on top of the elevated sandy soils has a lower risk of desiccation.

Subsurface groundwater flows in this area are relatively complicated due to the presence of a glacial moraine and valleys. The possible location to inject surface water is indicated with a green arrow in *figure 10* on the next page. This location results in transportation of water in the subsurface towards the west, where it reaches the surface again as a spring. Travel times within the subsurface are variable. They can vary between several months to several years (van Vught *et al.*, 2017a). Data on the travel time of water injected at this location is missing. When the amount of seepage in the west starts to overflow the surface area (due to the injected water) on a rate that is more than necessary to maintain natural habitats, the extraction rate at Manderveen can be increased to a level that brings seepage back to its current level.

To be able to calculate the **performance** of this solution, the depth of the groundwater table during drought periods has to be known. Unfortunately no data is available on the depth of this water table in the infiltration zone. But if it can be raised with 2 meters (Dinoloket) on the total area of 2.1 hectares (Natuur en Milieu, 2019) with a porosity of 0.38 (Leap and Kaplan, 1988), it can store: 21000*2,0*0,38 = 15.960 m^3 when saturated. It is guessed (since data is lacking) that this total injection of 15.960 m^3 can be done twice a year (because injected water is transported towards the seepage zone) resulting in a total of 31.920 m^3 that can be injected per year. This amount of water can also be extracting, when groundwater losses due to complicated groundwater flows are neglected.

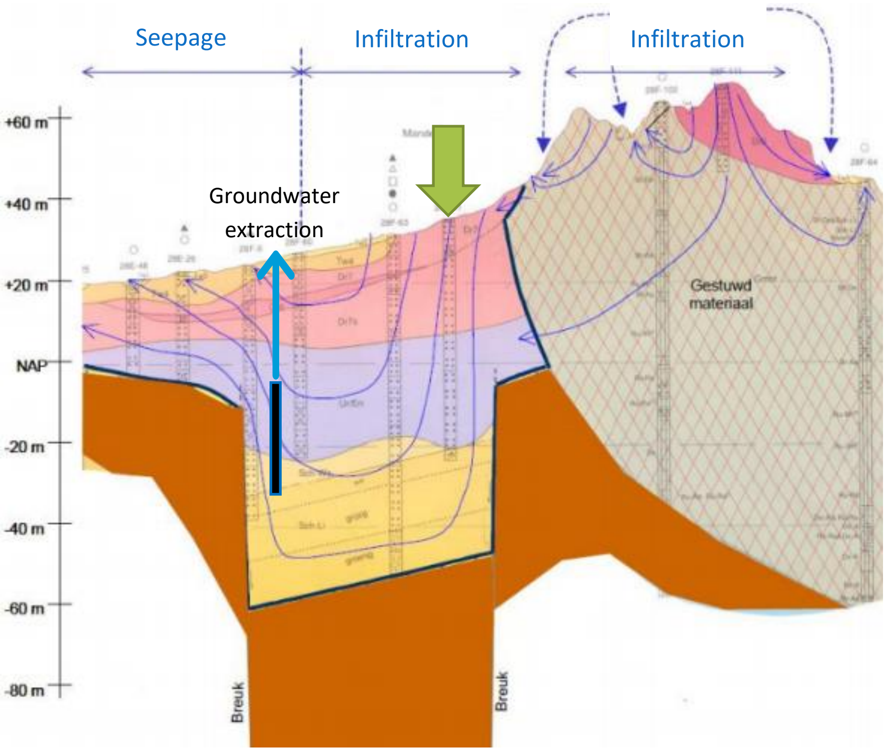

Figure 10 Simplified groundwater flow around the Manderveen extraction location (van Vught *et al.*, 2017a).

The transportation **costs** of water horizontally and vertically according to Zhou and Tol (2005) are visible in *table 3*.

Table 3 Operational costs of water transport according to Zhou and Tol (2005).

Distance (m)	Direction	Price
100	Vertical lift	0,05 €/m^3
100.000	Horizontal	0,05 €/m^3

This gives a total yearly OPEX of 251,37 €/year when water needs to be transported from the *Mosbeek* to the injection location, which is 15 m uphill and 750 horizontally (Google, 2020a). Data for capital expenses like piping or installation of pumps is not available.

Possible **risks** for this solution are contamination of the soil and groundwater in the Natura2000 area. The water from the *Mosbeek* has a different quality than the groundwater in the injection area, which is a risk and might result in the need for extra filtration steps after extraction or a pre-treatment before injection. Another risk are the complicated groundwater flows, which might result in a loss of injected water (according to Jan Hoogendoorn). Besides this, surface water extraction from the *Mosbeek* might have negative consequences for the area downstream of this creek.

3.1.2 INCREASING INFILTRATION BY REDUCING RUNOFF AND EVAPORATION ON FARMLAND

QUANTITY – EXTERNAL – STORYLINE 1, 2, 3 AND 4

After interviews with Jip Welkers and Jan Hoogendoorn, it became clear that within land surface hydrological processes, multiple external solutions exist that can be implemented at farmland. These external solutions help increasing the flexibility within groundwater extraction. One example of such a solution is reducing runoff and increasing the infiltration rate on surfaces that are subjected to relatively large amounts of runoff. This increases recharge of the water bearing aquifers with (rain)water instead of losing this water via runoff to rivers and eventually seas (Saifullah *et al.*, 2016). Nine possible methods to reduce surface runoff are investigated with a literature study (Sivanappan, 2006) and presented in *Appendix II*.

Another external solution to increase groundwater recharge is to reduce the evaporation of water on farmland. A reduction of evaporation results in an increase of recharge of the aquifer (Savabi *et al.*, 1989). Three possible methods (investigated by a literature study) to reduce evaporation of water are also presented in *Appendix II*:

From the presented methods in *Appendix II*, subsurface drip irrigation (SUbDI) will be quantified in this thesis research because, according to Van der Kooij *et al.*, (2013), subsurface drip irrigation is an important solution to solve quantity problems in the water crisis, because it is able to reduce surface runoff and evaporation and increases groundwater recharge. Besides that it has also the potential to increase crop yields per unit water. Another positive side effect of drip irrigation is a reduction of leaking of contaminants (nitrate from fertilizers, herbicides and pesticides) into surface waters due to surface runoff (Rathier and Frink, 1989). This results in higher quality surface waters. Due to these positive side effects, it is decided to quantify this promising solution of SUbDI in more detail.

When farmers install a SUbDI-system, a flexibility increasing solution is implemented at the source of the problem. Less water has to be purified and transported to farmlands (for irrigation) and farmers use less other sources of water (ground- and surface water), which results in a lager ground and surface water availability for Vitens. With this in mind it can be said that the installation of SUbDI-systems increases the flexibility of extractions of the "shallow groundwater extraction in a rural environment" archetype. The increase in groundwater recharge due to SUbDI, further increases this flexibility.

The **performance** of a drip irrigation system depends highly on local conditions like: soil type, climate, weather, initial irrigation system and crop. According to Valentín *et al.*, (2020), the amount of evaporation can be reduced by 40% when a SUbDI-system is used instead of irrigation with sprinklers on a maize plot in a semi-arid environment.

This reduction of evaporation results in a 19.557.502 m^3/year reduction in water use for agricultural businesses in the five provinces of Vitens, assuming similar conditions as Valentín *et al.*, (2020) describes and assuming that no SUbDI-systems are installed yet. Calculations and other relevant numbers can be found in the Excel file in *Appendix III*).

Information on the **costs** of a SubDI-system was available for a plot in the United States. The CAPEX of SubDI are 3880,17 € ha^{-1} and the OPEX is <40,39 € ha^{-1} $year^{-1}$ for a maize plot (Jacques *et al.*, 2018). The assumption is made that costs in the United states are similar as costs in the Netherlands. Besides that the reduction in labour costs due to the installation of a SUbDI-systems are not taken into account when calculating the OPEX.

A possible **risk** is that farmers are not willing to invest in a SubDI-system. This can be solved by granting subsidies.

3.1.3 INCREASING THE BUFFERING CAPACITY OF AGRICULTURAL SOILS (IBCAS)

QUANTITY – EXTERNAL – STORYLINE 1, 2 AND 4

Another external solution that is able to increase flexibility at shallow rural extractions, which can also be applied within agricultural land is increasing the buffering capacity of soils. Inspiration for this solution was gained from an interview with Jip Welkers. It is observed that rainwater cannot easily infiltrate into soils due to compaction of the soil (Batey, 2009). This compaction is caused by intensive processing, heavy machinery and animal hooves that apply pressure on the soil which reduces the pore volume in these soils (Wolkowski and Lowery, 2008). This decreases infiltration and the buffering capacity of agricultural soils. Rainwater will be trapped at the surface and flows towards diches from where it eventually flows away, which makes it useless for groundwater extraction. This results in a loss of precious fresh water and fertilizers for agricultural soils. The Dutch *Lumbricus Project* (Snellen, 2017) investigates which solutions can be applied on agricultural soils and what their effects are on the buffering capacity of these soils.

Soil improving solutions for agricultural soils according to the *Lumbricus Project* are:

1. Increasing the amount of organic matter in the soil by using compost. This organic matter functions as food for soil organisms that can increase the total pore space within a soil. It has been investigated by Kodešova *et al.*, (2006) that soils that are affected by soil organisms like earthworms, have a five times larger total pore space than soil that are not affected by soil organisms.
2. Reduce the acidity of a soil by applying lime (Goulding, 2016). Low acidities within agricultural soil also improve the living conditions of soil organisms and therefore increase porosity, infiltration and buffering capacities (Snellen, 2017).
3. Use agricultural machines that have wide tiers with low air pressure. These machines should use the same paths to drive on throughout the year and only in dry conditions in order to reduce pressure on the soil from the surface (Snellen, 2017).
4. Growing of crops that grow fast and have relatively deep roots. This has a beneficial effect on the soil structure since most of the biological life of a soil is located in the rhizosphere (Pierret *et al.*, 2007). And besides that, root channels enhance the flow of water in macropores and therefore increase infiltration rates (Wu *et al.*, 2017).

The knowledge on the **performance** of these solutions is limited, but the results of a Dutch project that is part of the *Lumbricus* project claim that a combination of soil improving solutions reduces the amount of required irrigation water with **33%** due to the increased buffering capacity of the agricultural soil (Stowa, 2015). This number was obtained in pilots in the Gelderse Vallei and the Achterhoek. These locations require less water that is withdrawn from surface waters and groundwater by farmers for irrigation. Besides that, they have a higher percolation rate towards water bearing aquifers. These two results of IBCAS-solutions are both beneficial for drinking water production. Besides this, surface water quality is also improved by these solutions, since surface runoff including pesticides, herbicides and fertilizers is limited. It is also hypothesized that increased infiltration and percolation towards water bearing aquifers, due to this higher buffering capacity of soils, results in higher amounts of natural filtration of this water, increasing groundwater quality. Precise data on this quality improvement and data on the quantity of water percolating to the water bearing aquifers is lacking (Stowa, 2015).

The 33% reduction of irrigation water saves (2086/19,5)*0,33 = 35,7 m^3 $year^{-1}$ ha^{-1}. This calculation is also based on agricultural data from *Appendix III*.

Data on **costs** of these solutions are highly variable and differ per location, therefore no numbers can be assigned to the CAPEX and OPEX of increasing the buffering capacity of agricultural soils. But it can be considered that application of these solutions should be seriously considered by farmers, since increased soil moisture contents result in higher crop yield, which (partly) compensates for the expenses (Snellen, 2017).

The only **risk** for this solution that is known, is the risk that farmers are not willing to invest in this solution. Subsidies from local or national governments might be required.

3.2 RIVERBANK FILTRATION

3.2.1 SURFACE WATER BUFFERS ALONG THE RIVER (VECHT) (SWB)

QUANTITY – INTERNAL – STORYLINE 1 AND 2

One possible way to store water during periods with high river discharges is by developing surface water basins in the riparian zone of a river. Inspiration for this solutions came from an interview with Joahnnes Dunnewolt. After this inspiring interview, al literature study was performed to elaborate this idea. Tan *et al.*, (2020) explains that little knowledge is available on the storing capacity of these kind of *floodplain lakes*. However, it is known that small lakes can be used for seasonal storage of water, which is considered useful for solving seasonal drought problems in the second storyline (Li *et al.*, 2019).This method of buffering water along rivers can be achieved by implementing measures that are also used in the "*Room for the River*" project (Rijke *et al.*, 2012). The two implementations that are necessary for development of these surface water basins along the river Vecht are relocation of the river dikes (further away from the river) and lowering of the floodplains in order to be able to be flooded every winter (high discharge period).

Since there is no literature available on successes of increasing extraction flexibility using such a surface water buffer nor data on their **performance**, it is decided by the author to calculate the possible performance of this new solution using the Water-Balance Approach described by Dingman, (2015). He describes that the water balance of water bodies (including lakes) can be described by:

$$E = P + Q\text{in} + GW\text{in} - Q\text{out} - GW\text{out} - \Delta S \qquad \text{(Eq. 2)}$$

In which E is the evaporation, P is precipitation, Q_{in} is the surface water inflow from river water during high river discharges, Q_{out} is the outflow of surface water from the basin, GW_{in} is the inflow of groundwater, GW_{out} is the outflow of groundwater and ΔS is the change in storage over time Δt.

For the calculation of the performance it is assumed that:

- There is no change in storage;
- Inflow of groundwater in the basin is zero, since it is assumed that groundwater is flowing towards the Vechterweerd extraction well (*figure 11*). GW_{out} in this figure is the amount of extra water available for the Vechterweerd extraction (compared to the regular groundwater flow in the current situation), which results in an increase in quantity flexibility.

- There is no surface water leaving the basin, the only pathways in which water can leave the basin are evaporation and infiltration into the groundwater.

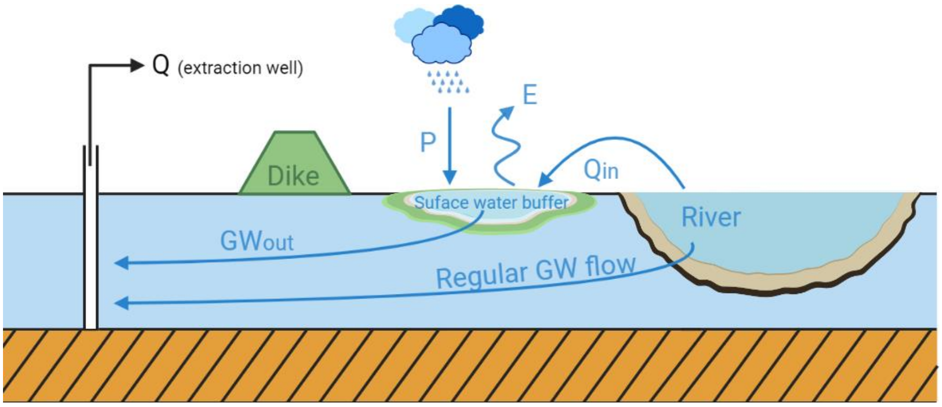

Figure 11 Schematic representation of water fluxes in and around an imaginary surface water buffer next to a river.

These assumptions and the equation from Dingman, result in the following simplified equation to calculate the extra aquifer recharge generated by the surface water buffer:

$$GW_{\text{out}} = P + Q_{\text{in}} - E \qquad \text{(Eq. 3)}$$

$P + Q_{\text{in}}$ can be calculated by calculating the total volume of the surface water buffer. The data used for this calculation is visible in *table 4*. To reduce complexity, it is assumed that the basin is filled once in winter with precipitation (P) and river water (Q_{in}) and that this water is used for recharging the aquifer in summer (GW_{out}).

Table 4 Values of parameters (including sources and calculations) for performance calculation SWB.

Parameter	Value	Source/calculation
Area of the basin	53.800 m^2	(Google, 2020b)
Basin depth	0,6 m	(Li *et al.*, 2019)
Volume (P + Q_{in})	32.280 m^3	53.800 * 0,6
Daily evaporation	0,4075 cm/day	(van Loon and Droogers, 2006)
Total Evaporation (E)	19.950 m^3	0,4075 * 0,01 * 53.800
GW_{out}	**12.330 m^3**	**32.280 – 19.950**

Evaporation in summer in the Netherlands can be 0,4075 cm per day (van Loon and Droogers, 2006). When it is assumed that evaporation only takes place during the 91 days of summer, the total evaporation can be calculated. This equals 0,4075*0,01*91 = 0,37 m per summer. This reduces the performance of these basins with 0,37 * 53.800 m^2 = 19.950,39 m^3. All parameters and calculations are summarised in *table 4*.

Possible **costs** include a 60 m southward relocation of the dike and floodplain lowering of 1 m (Google, 2020b). According to Waterschap Rivierenland, (n.d.), the installation of a new dike costs around 7,5 million euro per kilometre. The dike that has to be relocated is 410 meters long, which costs: 7,5*0,41 = 3,1 million euro. This number can be considered as a rough indication of the expected capital expenses, since precise data on costs of a dike relocation were not available. Nevertheless this number gives a serious indication of the order of magnitude of the costs of such a surface water buffer. Possible operational expenses consist of dredging of the basin due to sedimentation. This costs 2,50 €/m^3 of dredged material according to Bodemrichtlijn, (n.d.). Assuming a total of 100 m^3 (estimated due to lacking data) to be dredged per year, the yearly OPEX of a surface water buffer is around 250 €.

A major **risk** for the implementation of this internal solution, according to Martijn Mulder and Johannes Dunnewolt, is the risk of losing (part) of the natural attenuation in the aquifer due to reducing the residence time in this aquifer. This is caused by the decreased distance which groundwater has to travel from the surface water basin to the extraction well compared to the distance between the river and the extraction well. Besides that, farmers can also for this solution form a risk when they are not willing to sell parts of their land.

POSSIBLE VARIANT: INFILTRATION VIA RIVER ARM

A possible other variant of this surface water buffer is the implementation of a new river arm around the extraction location in order to increase the flexibility of the extractable quantity, without losing part of the natural attenuation in the aquifer. This can be developed by digging a river arm around the Vechterweerd extraction on the same distance as the extraction location is located from the main river (*figure 12*), in order to maintain the crucial 60 days presence of groundwater in the aquifer. In this figure, the blue arrows indicate new groundwater flows with the same travel time as the current groundwater flow. This results in an increase in flexibility of groundwater extraction, without quality loss.

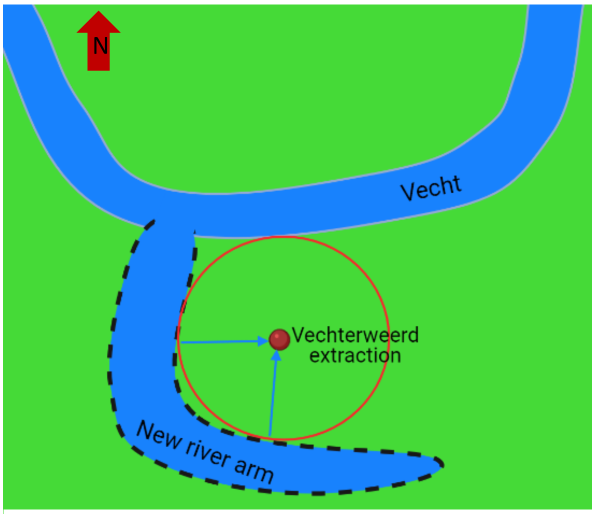

Figure 12 Schematic representation of a river arm around the Vechterweerd extraction location in order to be able to increase extraction rates.

This solution was not quantified due to the limited time for this project and will for that reason not be compared to other solutions.

3.2.2 RELOCATION OF EXTRACTION LOCATION (REL)

QUALITY – INTERNAL – STORYLINE 1, 2 AND 4

As described before, the transport of groundwater in an aquifer has the benefit of natural attenuation. According to Wang and Mulligan (2006), natural attenuation includes "*all types of processes that can reduce the concentration or minimize the toxicity of a contaminant*". When this occurs in a water bearing aquifer it has been proven that a longer residence time results in a greater degradation of organic contaminants like herbicides, pesticides and drug residues (Warren *et al.*, 2003) (Yang *et al.*, 2019). Yang *et al.* (2019) explains that there is a linear relation between the decreasing organic contaminant concentration (logarithmic scale) and time (*equation 3*).

$$\ln(C) = \ln(C_0) - kt \qquad \text{(Eq. 3)}$$

In this equation C is the concentration of organic contaminants in (µg/L) after time t (year), C_o is the concentration of organic contaminants at the beginning of natural attenuation processes and k is the attenuation rate constant of an aquifer. With this equation the performance of a relocation of the extraction location can be calculated.

This information was gained after a literature review. It suggests the idea that groundwater quality can be improved by increasing the residence time of groundwater in the water bearing aquifer. A possible internal solution to achieve this quality increase can be introduced: relocate the Vechterweerd extraction location.

To investigate the ability of the aquifer to naturally attenuate contaminations, the attenuation rate constant of a contaminant in the aquifer needs to be known. This k-value will be calculated for one problematic substance in the extracted water of the Vechterweerd location to be able to give a quantitative expression of the

performance of relocation of the extraction location. This contaminant is the anti-epileptic medicine Gabapentine (Gb). This contaminant was chosen, because this is considered to be a problematic contaminant in the river water of the Vecht and in the extracted groundwater. Besides that, all necessary data was available to calculate its k-value. Relevant concentrations and values of Gabapentine are visible in *table 5*. Other relevant parameters are: the travel time to the extraction location from the river, which is 60 days (van Vught *et al.*, 2017b) and the distance from the river towards the extraction location, which is 280,90 meter (Google, 2020b)

Table 5 Concentrations and values for the medicine Gabapentine.

Contaminant name	Source	Concentration in river water (location A)	Concentration at extraction (location B)	Signal value
Gabapentine	Medicine residue from RWZI	0,32 µg/l	0,14 µg/l	0,10 µg/l

$$K(Gb) = \frac{\ln(C_0)-\ln(C)}{t} = \frac{\ln(0{,}32)-\ln(0{,}14)}{(\frac{60}{365})} = 5{,}03\ \mu\text{g/l/year}$$

With this knowledge a plot was made displaying the decrease in contaminant concentration when the distance between the river Vecht and the extraction location (reactor length) increases (which also increases residence time in the aquifer). During the calculations is assumed that the aquifer is homogenous over its complete length and that flow velocities are constant everywhere in the aquifer. The plot is visible in *figure 13*.

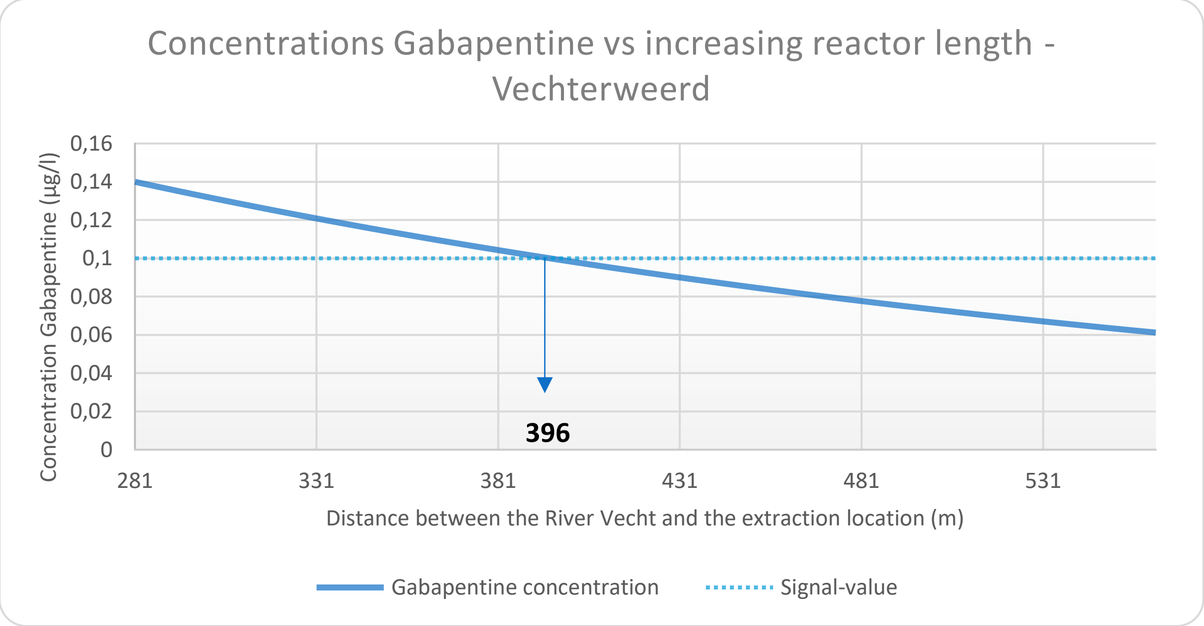

Figure 13 Concentrations Gabapentine vs increasing reactor (aquifer) length at Vechterweerd

In figure 15 is visible that a relocation of the extraction location at Vechterweerd away from the river Vecht results in a decrease in Gabapentine concentrations in the extracted groundwater. A relocation to 396 m away from the Vecht might even bring the concentration below the signal-value of 0,1 µg/l. This is a 12,5% increase in groundwater quality concerning Gabapentine compared to the current location of the Vechterweerd extraction.

According to Esther de Jong, there is no increasing trend visible in the contaminant concentration of the extracted groundwater. Therefore, there is no need to advise a relocation of the Vechterweerd extraction location further than 396 meter away from the river.

To be able to also give a quantitative expression of the performance of the natural attenuating ability of the aquifer for pesticides and herbicides, the same calculations can be conducted. This is not done in this thesis, since concentrations of the problematic crop protection substances chloradizone-desphenyl, dimethenamid and metolachlor in the river water of the Vecht are missing. These substances are also considered to be problematic at Vechterweerd (Steenvoorden *et al.*, 2021).

When considering a relocation of a riverbank filtration extraction location, one should consider the **costs** for such a relocation. It is expected by the author that costs are higher when the distance between a specific river and the extraction location is becoming greater. Besides the costs of relocation material and their installation, more land has to be protected against contamination, which might often mean that more land is becoming unusable for agriculture or other purposes (which is a **risk**, if farmers are not willing to sell their land). Data on the CAPEX of relocation of an extraction is lacking. Besides that, it is expected that yearly operational costs after relocation are roughly the same as before the relocation. Another risk can be found in a possible increase in soil contamination further away from the river with contaminants from the river water.

3.2.3 INCREASING NATURAL ATTENUATION EX-SITU: INJECTION OF RIVERWATER IN DUNES (RWID)

QUALITY – EXTERNAL - STORYLINE 1, 2, 3 AND 4

Filtration of river water with the natural attenuating ability of soils can also be done externally. This became clear after the interview with Stefan Jansen. In the western part of the Netherlands surface water from rivers and the IJsselmeer is transported to and injected into coastal dunes in order to reduce the concentration of organic contaminants (Stuyfzand, 2015). The same concept can also be applied by infiltrating (pre-treated) river water into sand bodies. These sand bodies can be dunes, aquifers or artificial sand bodies.

Previous studies gave an indication of the **performance** of this solution. It has shown that injection of pre-treated riverwater in the dunes of Castricum, results in major reduction of contaminants. Nitrate can be reduced from 22,5 mg/l to 6,4 mg/L (Piet and Zoeteman, 1980). That is a reduction of 71,6 %. This method is also able to remove organic contaminants like drugs (Jaksic, 2010), heavy metals, bacteria and viruses (Hiemstra and Buiteman, 2001). Percentages of contaminant reduction differ per contaminant and are not further investigated due to the limited time for this research. A quantification of **costs** is also not performed in this research, due to the lacking knowledge on the presence of suitable sand bodies for water injection in the five provinces of Vitens.

Also here, the **risk** exists of contaminating the external system when surface water is injected. This might require additional pre-treatment steps before injection.

3.3 GENERAL SOLUTIONS FOR BOTH THE ARCHETYPES

3.3.1 INCREASING NATURAL ATTENUATION IN-SITU: PERMEABLE REACTIVE BARRIERS (PRB)

QUALITY – INTERNAL - STORYLINE 1, 2, 3 AND 4

From the same interview with Stefan Jansen, another possible internal solution was discussed to increase groundwater quality: permeable reactive barriers. For this solution a reactive media is placed perpendicular to the contaminated groundwater flow. This natural groundwater flow forces the contaminants to react with the media to a product that is less harmful or to be fixed to the barrier, both result in a higher quality of groundwater at the extraction well (Obiri-Nyarko, 2014).

One possibility is to transform nitrate (NO_3^-) to nitrogen gas (N_2) by denitrification (*equation 4*):

$$2NO_3^- + 10\ e^- + 12\ H^+ \rightarrow N_2 + 6\ H_2O \qquad \text{(Eq. 4)}$$

For this reaction, denitrifying microbes require carbon (C) as a source of energy. This can be provided in the form of wood fragments (Schipper *et al.*, 2010). The **performance** of PRB is according to Gibert *et al.*, (2019) and Schipper and Vojvodić, (2001) for the removal of nitrate around 70-95% when the input is between 22-71 mg nitrate per liter (50 mg/L nitrate in groundwater at Manderveen). This removal brings the nitrate concentration far below the signal values that are defined. Besides that, this method to improve groundwater quality is known for being inexpensive. Installation of a 17,2 m^3 barrier **costs** €2722 and maintenance costs are low (< €100). This barrier should have a life time of 20 years. The scope of this research is 100 years, this results in a total of €13.610 (Schipper *et al.*, 2010). Besides this application for the removal of nitrate. Permeable reactive barriers can also be used for the removal of other contaminants that are sensitive for redox-reactions. These are: pharmaceuticals, pesticides, herbicides and heavy metals (Schipper *et al.*, 2010) (Moraci & Calabro, 2010), which makes this solution useful for groundwater quality improvement for Manderveen and Vechterweerd. Assumed for this results are that site characteristics are the same as in Gibert *et al.*, (2019) and similar installation cost in the Netherlands as in the US.

A **risk** can be seen in the need for an extensive study of the area before installation. Such a study has to be performed on the site characteristics (hydrologic aspects, contaminants, soil characteristics) because every site has specific needs and limitations. This might increase the costs for this solution.

3.3.2 AQUIFER STORAGE RECOVERY (ASR)

QUANTITY – EXTERNAL - STORYLINE 1, 2 AND 4

In interviews with Linda Maring and Hilde Passier the concept of aquifer storage recovery (ASR) was discussed. This is an external solution that is capable of solving one of the most fundamental quantity problems in the Netherlands: seasonal differences in freshwater supply (Maliva, 2006). The concept of ASR includes storage of water in aquifers when there is a surplus in (freshwater) supply. This stored water can be recovered during periods when demands are higher and the supply is insufficient (Ward *et al.*, 2009).

Throughout one year, the Netherlands receives 105 billion square meters of fresh water, through rivers and precipitation (Witte, 2020). During periods with a relatively high supply rate, water is transported as fast as possible towards the sea. This high discharge of water is necessary to reduce flood risks. But can also be seen as a solution to reduce drought damage in dry periods and to produce drinking water.

To be able to use excess water from wetter periods in drier periods a storage aquifer is needed to be able to apply the concept of ASR. This aquifer is preferably located below an relatively high elevated area like the Veluwe, the Sallandse heuvelrug or the Utrechtse Heuvelrug. These areas have a relatively deep water table and have for that reason a higher storage capacity on top of the current water table (*figure 14*) (Deltares, 2020).

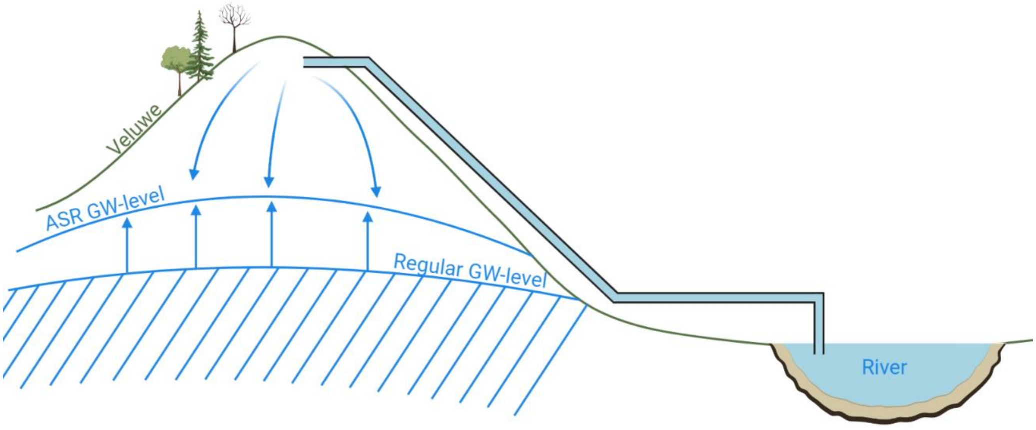

Figure 14 Schematic representation of the storage capacity of the Veluwe for ASR.

The possibilities of a large scale injection of river water below the Veluwe is investigated by Deltares in a project called: *De Nationale Gieter* (The National Watercan). The Veluwe is the area that has the largest storage capacity in the five provinces of Vitens. Its possible **performance** has also been quantified. It is able to store 0,5% of the yearly river discharge, which is 300 million m^3 per year (Deltares, 2020). The **costs** of recharging an aquifer are around 0,25 euro per cubic meter. Which is a total of €75 million per year (Peters, 2020). The capital expenditures for such a solution are not available.

This solution can supply relatively large quantities of fresh water during drier periods, but is not without **risks**. River water is often contaminated. This, also here, introduces the risk of contamination of the soil of these higher elevated natural areas. It is assumed that different pre-treatment steps are necessary before river water can be stored in an aquifer. Possible benefits of ASR are: a lower risk of desiccation of natural areas and improvement of water quality due to natural attenuation in the aquifer.

3.3.3 ALTERNATING BETWEEN SHALLOW- AND DEEP GROUNDWATER EXTRACTION (SDE)

QUANTITY – INTERNAL – STORYLINE 2 AND 3

The inspiration presentations about flexibility in nature and the human brain explained that flexibility can also be gained, by being versatile. This information was further elaborated in a literature study.

Evans & Bahrami (2020) also explain that flexibility during a crisis can be increased by being versatile. Their example of a crisis is the *Coronavirus* pandemic. Flexibility in such a crisis can be increased by: "*being able to switch gears, wear different hats and be competent in several domains*". This third concept can also be applied on multiple levels in the drinking water production process of Vitens. As already explained, Vitens uses six different archetypes to produce drinking water. Combining these different archetypes can result in a higher level of flexibility of the drinking water production of Vitens. For example an archetype that is able to extract water in summer can compensate for the shortages other archetypes experience during these periods. There are multiple combinations and alternations possible between different extractions, but one that is most relevant for the archetypes that are investigated in this thesis research, according to the author, is alternating between shallow and deep groundwater extraction.

It is known that groundwater levels fluctuate throughout the year, with relatively shallow water tables during wetter winters and deeper water tables in relatively drier summers (Cavazza *et al.*, 2007). For this reason it can be considered to only extract shallow groundwater during wetter periods and to shift to groundwater extraction from a deep aquifer during drier periods. When this is done, the risk of desiccation of nature reserves and agricultural lands is reduced, since plants are only dependant on relatively shallow groundwater because roots of crops and trees do not reach into the deeper aquifers.

This internal solution can be applied at the Vechterweerd extraction location, since water here is extracted from a shallow aquifer (0 – 35 meters below the surface). Seasonal shifting or shifting during extreme droughts to the deeper aquifer at Vechterweerd (80 – 210 meters below the surface) can be a solution to ensure a constant supply of groundwater for drinking water production purposes without the risk of desiccation of the above ground nature and agriculture.

Land subsidence becomes a major **risk** when aquifers are overexploited (Galloway and Burbey, 2011). Nevertheless, Galloway and Burbey, (2011) state that land subsidence effects are minimal, when seasonal drawdown (lowering of the hydraulic head within an aquifer due to groundwater extraction) is limited below 30 meters. And that after a drier season when water has been extracted, a wet season follows in which no extraction occurs and the hydraulic head can recover to its original level.

The potential **performance** of extraction from the deeper confined aquifer at Vechterweerd can be calculated using the *Thiem equation* (*equation 5*). Since data of the source of the groundwater in the deeper aquifer is lacking, we assume that the deeper aquifer is recharged from the confining layer above. This also allows the use of *Thiem equation*:

$$Q = \frac{2\pi k D(h2 - h1)}{\ln\left(\frac{\lambda}{r}\right)} \qquad \text{(Eq. 5)}$$

In which Q is the well discharge rate (m^3/d), k is the permeability (m/d), D is the thickness of the aquifer (m), (h2 – h1) is the aquifer drawdown (m) and λ is the horizontal distance to the maximum distance of measurable drawdown (m), also called the influence distance and r is the borehole radius (m) (Bouwer and Rice, 1976). A visual representation of these parameters is visible in *figure 15*. Note that in this calculation of the extraction potential is chosen to extract groundwater using a fully penetrating well and that it is assumed that the groundwater table of the shallow aquifer is not affected during extraction from the deep aquifer.

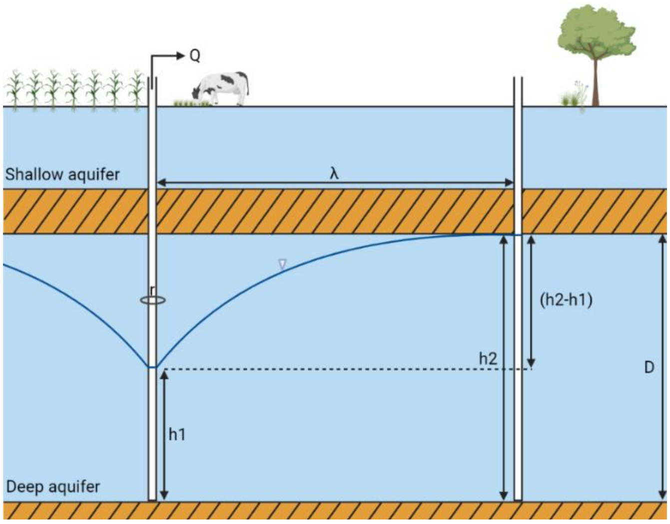

Figure 15 Schematic representation of parameters related to drawdown in the deep aquifer at Vechterweerd (not to scale).

The influence distance λ is also unknown for the possible extraction in the deeper aquifer at Vechterweerd. For this reason it is assumed that λ is the minimum value as described by Huisman, (1972). He states that *Thiems equation* can only be applied if $\lambda > 3 * D$. This gives a minimum value of $3 * 130 = 390\,m$. Besides that, it is assumed that at the start of groundwater extraction the deep aquifer is fully saturated (h2 = D). Other data that is used for the calculation of the performance of the deep aquifer is visible in *table 6*.

Table 6 Parameter values and their sources for the deep aquifer at Vechterweerd.

Parameter	Value	Source
K	3,75 m/d	Dinoloket
D	130 m	(van Vught *et al.*, 2017b)
(h2-h1)	30 m	(Galloway and Burbey, 2011)
λ	390 m	(Huisman, 1972)
r	0,11 m	(Claesson and Eskilson, 1988)

Solving *equation 5* with the values from *table 6*, gives a possible extraction rate of 11.242,7 m^3/d. This value is considered to be roughly correct, since this results in a total yearly extraction of 4,1 million $m^3/year$. This number is in the same order of magnitude as the already known possible extraction rates in the shallow aquifers of Manderveen and Vechterweerd. To reduce the risk of land subsides, the extraction from the deep aquifer at Vechterweerd can only be used during the drier 6 months of a year with a pumping rate of 11.242,7 m^3/d. This results in a possible maximum total yearly extraction of 2.1 million m^3/year. In reality this number will be lower, since extraction is only necessary during extreme drought periods.

According to Johannes Dunnewolt, another **risk** when extracting from a deep aquifer is salinization of the groundwater and eventually extraction of saline or brackish water for drinking water production. This risk is lower when extraction rates are lower. For this reason he considers that shifting to a deeper aquifer can be an interesting solution only during dry periods. This dealing with possible salinization is, according to him, also the main concern when adjustments need to be made to the existing extraction well. The **costs** of an additional system for desalinization are investigated in a literate study. CAPEX are highly dependent of the salinity of the groundwater. Desalination systems handling brackish water are less expensive that systems that work with saline water. It is assumed that due to lower extraction rates, only brackish water is extracted from the deeper aquifer at Vechterweerd. The CAPEX is also dependant on the scale of the desalination plant. According to Arroyo & Shirazi (2012), capital expenses for desalination of brackish groundwater are around 2,97 USD/US gal (of daily production capacity), which is equal to 650 €/m^3. This number gives a total CAPEX of **7.307.300 €.** The data on the lifetime of such a system is not available.

OPEX are €0,62/m^3 (Ziolkowska, 2015). This results in a total of **1.302.000 €/year** (mainly due to high energy consumption and replacements of membranes).

Precise data on the salinity of deep aquifer water and information on the presence of other contaminants in the deeper aquifer (which requires more additional filtration steps) is not available.

Other **risk** that need to be considered (according to Martijn Mulder) are:

- Phreatic lowering in regions further away from the Vechterweerd, where confining layers end.
- In eastern parts of the Netherlands, the geohydrological base is more shallow than in western parts of the Netherlands (in Utrecht and Friesland around 200 m below the surface but at the German border only 50 m below the surface). This limits this solution in the east because there is a limited amount of deep aquifers or there might not be deep aquifers at all.

3.4 SUMMARY OF RESULTS

The results of nine quantified solutions described in the sections above are summarised in *table 7* and displayed in *figure 16-18* on the next pages.

Solution	Main class	Subclass	Storylines				Performance	Costs	Risks	Missing data
Abbreviation	**Quality/ Quantity**	**Internal solution/ External solution**	**1**	**2**	**3**	**4**		**CAPEX (€)** **OPEX (€/year)**		
SW N2000	Quantity	External solution	x	x		x	**31.920 m^3/year**	Unknown **251,37 €/year**	1. Contamination of the groundwater in natura2000 area 2. Loss of water due to complicated groundwater flows and travel times 3. Negative consequences for the area downstream of the *Mosbeek*	1. Precise porosity data 2. Exact flow velocities 3. Groundwater flow directions 4. Depth water table 5. Amount of possible injections per year 6. Capital expenses
SUbDI-system	Quantity	External solution	x	x		x	**19.557.502 m^3/year** **=** **41,96 m^3/ha/year**	**1.808.562.758 €** **18.825.940,6 €/year** **=** **3880,17 €/ha** **< 40,39 €/ha/year**	1. Farmers are not willing to invest in such a project	1. Local condition for soil type, climate, weather, initial irrigation system and crop 2. Dutch price indications 3. Lifetime of a SubDI-system 4. Surface runoff reduction caused by a SubDI-system
IBCAS	Quantity	External solution	x	x		x	**16.639.912,8 m^3/year** **=** **35,7 m^3/ha/year** (+ percolated water towards water bearing aquifer)	Unknown Unknown	1. Farmers are not willing to invest in these solutions	1. Local effects of soil improving solutions on percolation towards the water table and recharge of water bearing aquifers. 2. Quality effects of increased filtration of percolating water 3. Amount of water percolating to the water bearing aquifer 4. Financial data
SWB	Quantity	Internal solution	x	x			**12.330 m^3/year**	**>€ 3.100.000** **250 €/year**	1. Farmers are not willing to sell parts of their land. 2. Surface waters are located closer to the extraction location, reducing the amount of bank filtration, lowering the quality of the groundwater.	1. Dike relocation prices 2. Prices for lowering of a floodplain 3. Yearly dredged volume.

REL (115 m away from the Vecht)	Quality	Internal solution	x	x		x	**12,5%** contaminant reduction	Unknown The same as before relocation	1. Farmers are not willing to sell their land 2. More soil contamination by contaminants from the river Vecht	1. Concentrations of chloradizone-desphenyl, dimethenamid and metolachlor in the river water of the Vecht 2. CAPEX of relocation 3. Current OPEX data for the Vechterweerd location
RWID	Quality	External solution	x	x	x	x	**71,6 %**	Unknown Unknown	1. Contamination of dune systems	1. OPEX transport costs 2. CAPEX pipes
PRB	Quality	Internal solution	x	x	x	x	**70-95%** contaminant reduction	**€13.610** **<100 € year^{-1}**	1. Extensive study required	1. Specific location data
ASR	Quantity	External solution	x	x		x	**300.000.000 m^3/year**	Unknown **75.000.000 € year^{-1}**	1. The subsurface of the Veluwe can become contaminated due to injection with water from another location	1. Capital expenses for the development of a transportation system 2. Amount of km of infrastructure already available for water transport
DSE	Quantity	Internal solution		x	x		**2.100.000 m^3/year**	**7.307.300 €** **1.302.000 €/year**	1. Land subsidence 2. Salinisation of deep groundwater 3. Phreatic lowering in regions further away from the Vechterweerd, where confining layers end 4. Depth of the geohydrological base	1. Source of recharge of the deep aquifer 2. The influence distance of drawdown at Vechterweerd 3. Precise salinity of extracted groundwater from the deeper aquifer 4. Lifetime of a desalinisation system. 5. Presence of other contaminants in the deeper aquifer

Table 7 Summary of the gathered data of nine quantified solutions that are able to increase flexibility within groundwater extraction at two archetypes of Vitens

3.5 VISUALISATION AND RANKING

List of solutions

Besides the quantified solution presented in *table 7*, more solutions are presented in this results section. An overview of all solution is visible in *table 8*, in which the solutions that are not quantified are highlighted in yellow.

Table 8 All possible solutions provided in the results section

Name	Quality/Quantity	Internal/External
Groundwater injection in N2000 area	Quantity	External
Reducing runoff using (eight) different farming techniques	Quantity	External
Reducing evaporation using (two) different farming techniques	Quantity	External
SUbDI-systems	Quantity	External
Increasing the buffering capacity of agricultural soil	Quantity	External
Surface Water buffer	Quantity	Internal
New river arm around extraction	Quantity	Internal
Relocation of the extraction location	Quality	Internal
Permeable reactive barriers	Quality	Internal
River water injection in dunes	Quality	External
Aquifer Storage Recovery	Quantity	External
Alternating deep- and shallow extraction	Quantity	Internal

This yellow solutions were not quantified due to the limited time for this thesis research. For this reason, their efficiencies could not be calculated and they were not included in rankings.

Quantity Solutions

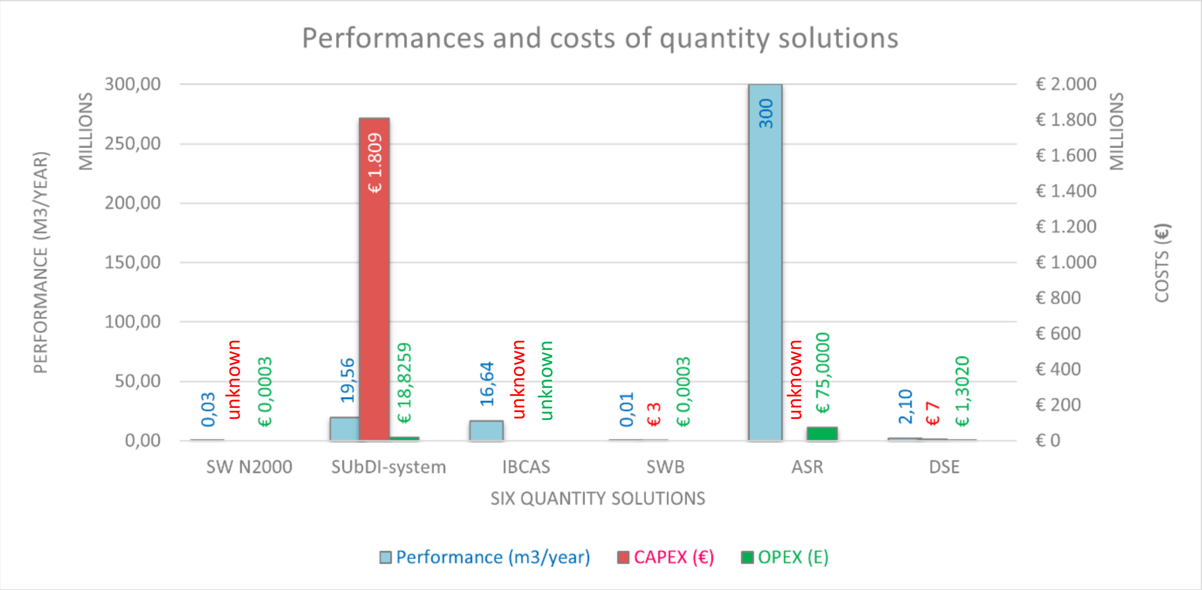

Figure 16 Bar chart displaying the performance, CAPEX and OPEX of 6 quantity solutions.

From *figure 16* it becomes clear that it is hard to compare the efficiency of the six different quantity solutions, due to different scales they operate on. For example the performance of the ASR solutions (300 million m^3/year) is a solution that can be implemented on a national scale, while SWB (12.330 m^3/year) is a small scale local solution. For this reason, a new bar chart was made displaying the costs per cubic meter water that the solution produces (calculated using *equation 1*). This bar chart is visible in *figure 17*. It was chosen to neglect capital expenses when plotting this figure, since too much numbers where lacking to make a well-founded comparison. Besides that, financial information of the IBCAS solution was also lacking and is for that reason not plotted in figure 17 and not included in the ranking of the quantity solutions.

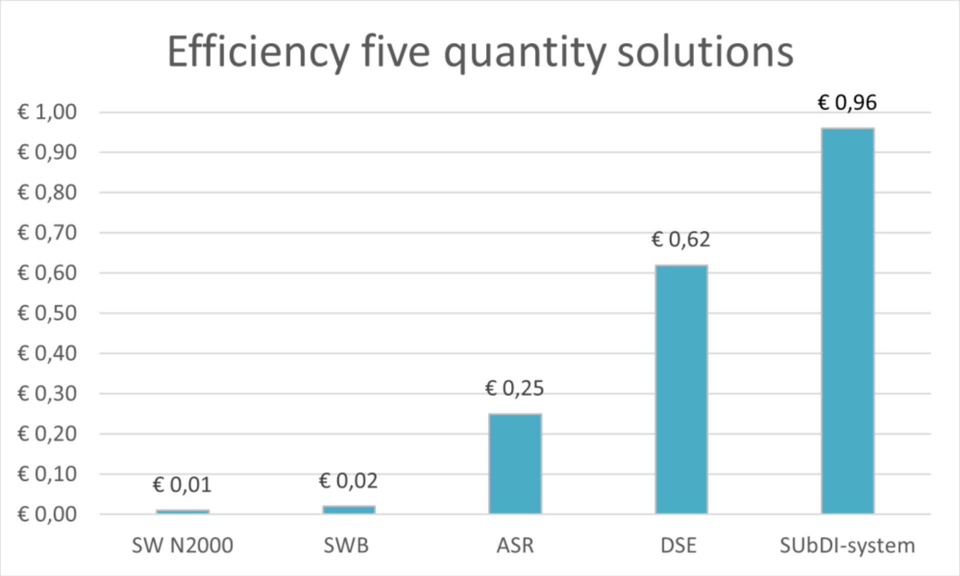

Figure 17 Costs of a cubic meter of water for five quantity increasing solutions (calculated by dividing their yearly OPEX by their yearly performance). The horizontal blue line indicates the current price Vitens asks for one cubic meter of drinking water.

By analysing the values displayed in *figure 17*, a ranking of the five quantity solutions can be made based on their efficiency. Solutions that have the lowest price for 1 cubic meter of water are considered to be most efficient and solutions that have the highest price are considered to be less efficient. This resulted in the ranking visible in *table 9*.

Table 9 Ranking of the quantity solutions (from most to least efficient).

Rank	Solutions
1	Groundwater injection in Natura2000 areas at Manderveen
2	Surface water buffers at riverbank filtration extraction locations
3	Aquifer Storage Recovery below the Veluwe
4	Alternating between deep and shallow groundwater extraction
5	Subsurface drip irrigation systems in shallow rural extraction areas
?	Increasing the buffering capacity of agricultural soils

Quantity Solutions

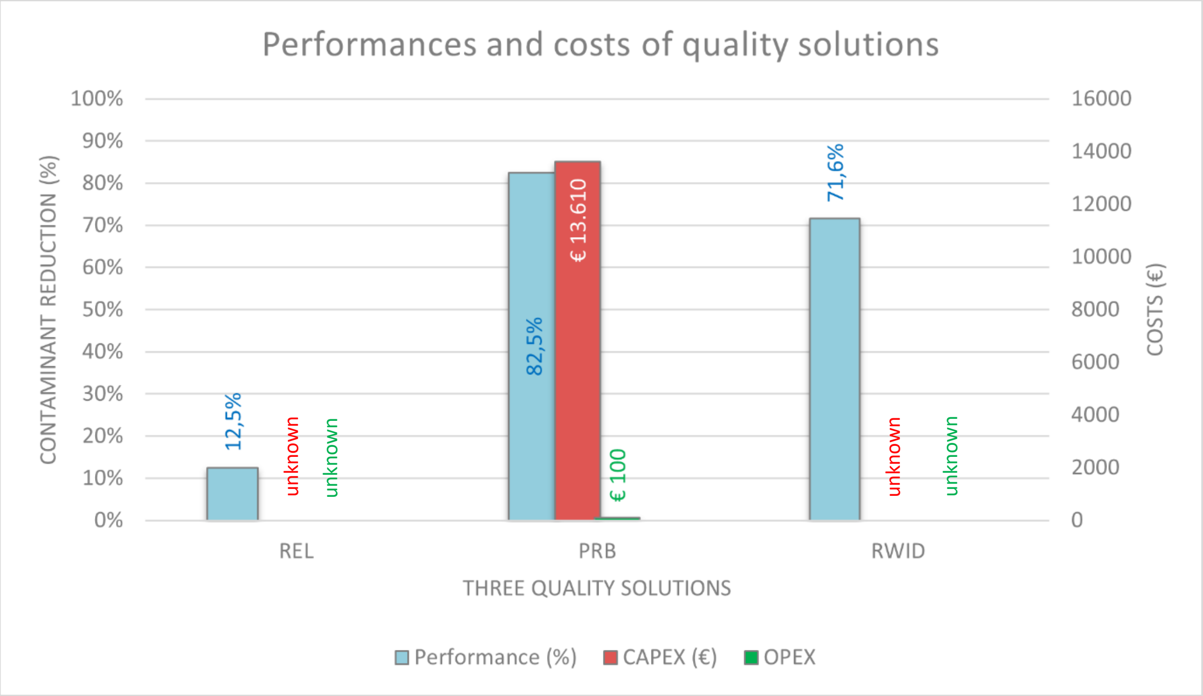

Figure 18 Bar chart displaying the performance, CAPEX and OPEX of 3 quality solutions.

The efficiency of the quality solutions from figure 18 was not calculated due to the missing financial data of most of the solutions. For this reason it was also impossible to make a well validated ranking of these solutions.

4 DISCUSSION

4.1 RELIABILITY

The reliability of the used method for selecting, classifying and ranking the nine different quantified solutions had to be discussed before conclusions for this research could be drawn.

In the **first step** four criteria were used for the selection of the flexibility increasing solution. These were: 1) no deterioration of drinking water quality; 2) no deterioration of drinking water quantity; 3) improving adaptation ability and 4) improving resilience. For a solution to be selected it should meet criterion 1 or 2 and criterion 3 or 4. When reflecting on this selection procedure it became clear that criterion 1 and 2 are clear criterion, because they help the convergence towards solutions that are within the scope of this research. It was also realized that it is hard to use criterion 3 and 4, since scientific literature does often not clearly state whether a solution meets these criterion or not. In this thesis research solutions are therefore often selected based on the authors judgement if a solutions increases adaptation ability or resilience or none.

The classification framework that was used in the **second step** clearly defines if a solution helps in creasing flexibility in future groundwater quantity or quality and if a solution can be implemented internally or externally. It is considered that these two classes can be a start for the development of a toolbox in which a fitted solution can be found for an observed problem. The subclass distinguishing between the different storylines turned out to be less relevant for this toolbox, since most of the solutions have the ability to improve multiple storylines. This makes the storyline sub class less relevant compared to the other two classes. Besides its relevance, the reliability of the classification of the solutions in the four storyline sub classes is also an interesting topic for discussion. This is because scientific literature does not clearly state which storyline a specific solution is aiming to improve. For this reason, classification into these four sub classes is again based on the authors judgement.

In the **third step**, the reliability of the quantitative data of the individual solution highly depends on the amount of missing data (which required more assumptions) and on the probability and impact of solution-specific risks. The efficiency calculations are based on the performance and OPEX data only, due to the missing CAPEX data and lifetime data of multiple solutions. This method is assumed to be less precise that a method including this CAPEX and lifetime data. It is known that this method will increase the total costs (CAPEX + OPEX in 100 years) for each solution and therefore result in another efficiency value than is calculated in this research. This might also change the ranking of the solutions. The risks of a solution can also highly affect its efficiency. For example at SW N2000, large amounts of injected water can be lost due to complicated groundwater flows, which makes the solution highly inefficient. This can also affect the current ranking. A good thing about ranking the solution using efficiencies in €/m^3 is the possible comparison between solutions that operated on different scales.

With all these uncertainties in mind, one may conclude that, the quantified results of this study can be used only as a first rough estimate of performances and costs. This may still be valuable as it may help Vitens and Deltares to decide which solutions are worth further investigation.

4.2 SUGGESTIONS FOR IMPROVEMENT

The previously determined weaker points in the used method allow multiple suggestions for improvement. Some of them are easy wins and some are more complicated suggestions and require more research.

Criterion 3 and 4 are suggested to be removed in the **first step**, since they do not contribute to a scientifically based convergence towards flexibility increasing solutions. Instead of these two criteria a new criterion is suggested to be added: “reducing the impact on the environment” . This new criterion allows other solution to be selected that do not necessarily improve quantity or quality, but might reduce the impact of groundwater extraction on the environment. During this thesis research became clear that extraction location have a limited yearly extraction rate (or are closed), due to the impact on the environment. When this impact is reduced, specific extraction location can have a higher yearly extraction rate (or can stay open), which results in a higher flexibility within groundwater extraction for drinking water production.

The storyline sub class in the **second step** can be removed because it does not clearly distinguish which problem is solved by implementing a specific solution. Instead of these storylines, specific problems need to be determined for which a fitting solution can be found. These different problems can each form an individual sub class. The development of these new sub classes requires much more research to determine what these precise future problems are and is therefore considered to be time consuming.

In the **third step** multiple suggestions for improvement can be made. Firstly, more time needs to be invested in the investigation of the currently missing data (this can be an easy win). Serious improvements in the reliability of the quantitative data can be made when less assumptions have to be made and the efficiency is calculated by adding CAPEX data of a solution (*equation 6*). To give an even better indication of efficiencies of different solutions, the investigated risks should be quantified as well. This can be done by identifying the costs for risk reduction and its total impact (within 100 years). The reduction of the performance of a solution caused by a risk should be subtracted from the initially calculated performance. Besides that, risks can also cause an increase in costs (for example for carrying out pre-treatments before injecting surface water for ASR). These costs (for 1 year) should be added to the yearly OPEX. This improved method for calculating the efficiency of a solution is visible in *equation 6*.

$$Efficiency\ (\frac{€}{m^3}) = \frac{\left(\frac{Total\ 100\ year\ CAPEX}{100\ years} + Yearly\ OPEX + \frac{Total\ costs\ risk\ reduction\ for\ 100\ years}{100\ years}\right)}{Yearly\ \ performance - Performance\ reduction\ caused\ by\ risks} \qquad \text{Eq. 6}$$

The improvements can also be conducted for the quality improving solutions. The efficiency will then be calculated in €/% contaminant reduction.

4.3 ZOOMING OUT TO SEE MORE OPPORTUNITIES

This first exploration of flexibility increasing solutions gives a good indication of the different types of solutions that can be implemented. It is assumed that these solutions are capable of solving the problems that are described in the four storylines and that they can solve current and future deficits in drinking water quality and quantity in the five provinces of Vitens.

During the continuation of the “Flexible Groundwater Extraction” project, employees of Vitens and Deltares should consider that there are different domains in which an increase in flexibility can be achieved. There are considered to be three domains where solutions can be developed, these are:

At the source of a problem: here external solutions can be implemented. Farmers can reduce the use of pesticides, herbicides and fertilizers while implementing solutions that increase groundwater recharge. Other external solution can aim at reducing the impact on nature areas and therefore allow for an increase in extraction rate.

In situ. Here, internal solutions are dominant that are implemented in and the extraction location. Problems can be solved by for example adding additional filtration steps (solving quality issues) or increasing water availability using locally buffered water. Multiple solutions presented in this thesis aim to increase the yearly buffering capacity in the five provinces of Vitens. Throughout a year enough water flows through this area. It is the biggest challenge to collect it and store it for drier periods. If this can be done, future quantity issues can be solved.

At customer level. This last domain is beyond the scope of this research, but is considered to be an important opportunity for increasing flexibility. If customers of Vitens are more aware of the value of water and save more water (especially during drier periods) flexibility can be increased with relatively little effort.

These different opportunities are visualized in *figure 19* and additional solutions that are beyond the scope of this research, but considered to be useful in the future, are summarised in *Appendix IV*.

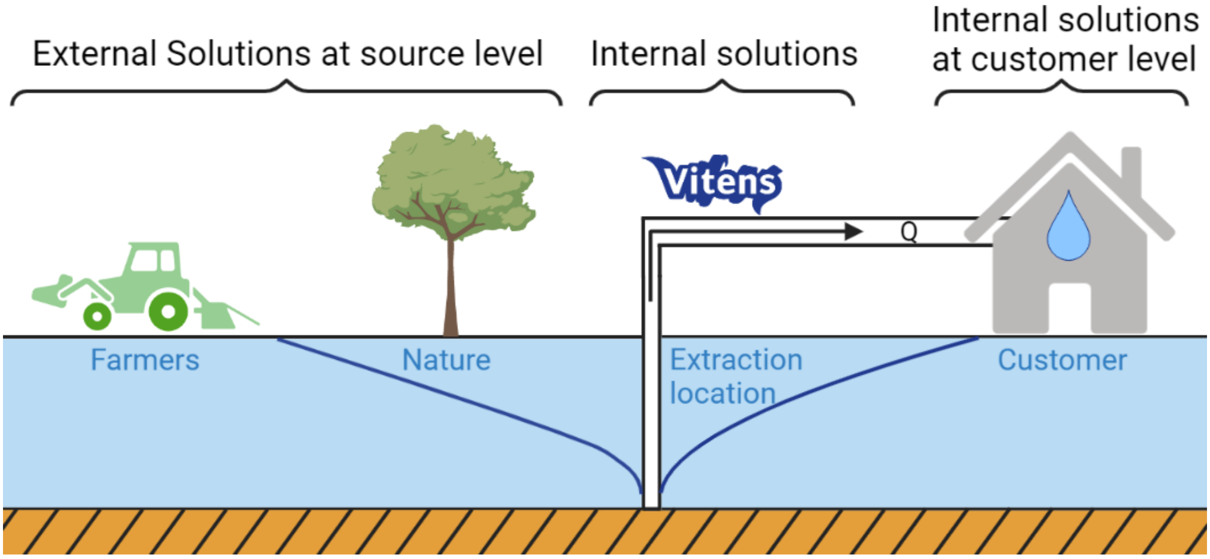

Figure 19 Different locations for the implementation of flexibility increasing solution.

5 CONCLUSION

With the used method for this thesis research an answer can be given to the question: *What flexible groundwater extraction solutions are most efficient when coping with expected future shocks at the shallow rural- and riverbank-filtration extraction locations of Vitens?* The answer to this question is a list of 12 different quality and quantity solutions that can be implemented internally or externally (*table 8*) from which five are successfully tested on their efficiency and ranked (*table 9*). Injection of surface water into Natura 2000 areas is considered to be the most efficient using this quantification method. The results of this thesis research can be used as a first exploration for possible flexibility increasing solutions for the groundwater extractions of Vitens. Besides this, the used method for solution selection, classification and testing gave an impression of the strong and weak point of this method, which should be taken into account during further investigation in the “Flexible Groundwater Extraction” project.

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APPENDIX I - LIST OF EXPERTS

Expert name	Expertise
Rianne van den Meiracker	Soil and groundwater quality Deltares
Jip Welkers	Sustainable environment (Vitens)
Stefan Jansen	Soil and groundwater quality (Deltares)
Mark Niesten	Subsurface and spatial planning (Deltares)
Linda Maring	Subsurface and spatial planning (Deltares)
Sjors de Vries	Spatial planning (Ruimtevolk)
Hilde Passier	Geochemistry (Deltares)
Rian Kloosterman	Hydrology and infrastructure (Vitens)
Anne Immers	Ecology (Vitens)
Johannes Dunnewolt	Hydrology at Vechterweerd (Vitens)
Martijn Mulder	Hydrology at Vechterweerd (Vitens)
Jan Hoogendoorn	Hydrology at Manderveen (Vitens)
Esther de Jong	Environmental manager Manderveen and Vechterweerd (Vitens)

APPENDIX II – SURFACE RUNOFF AND EVAPORTATION RUDUCING METHODS

Surface runoff reducing methods:

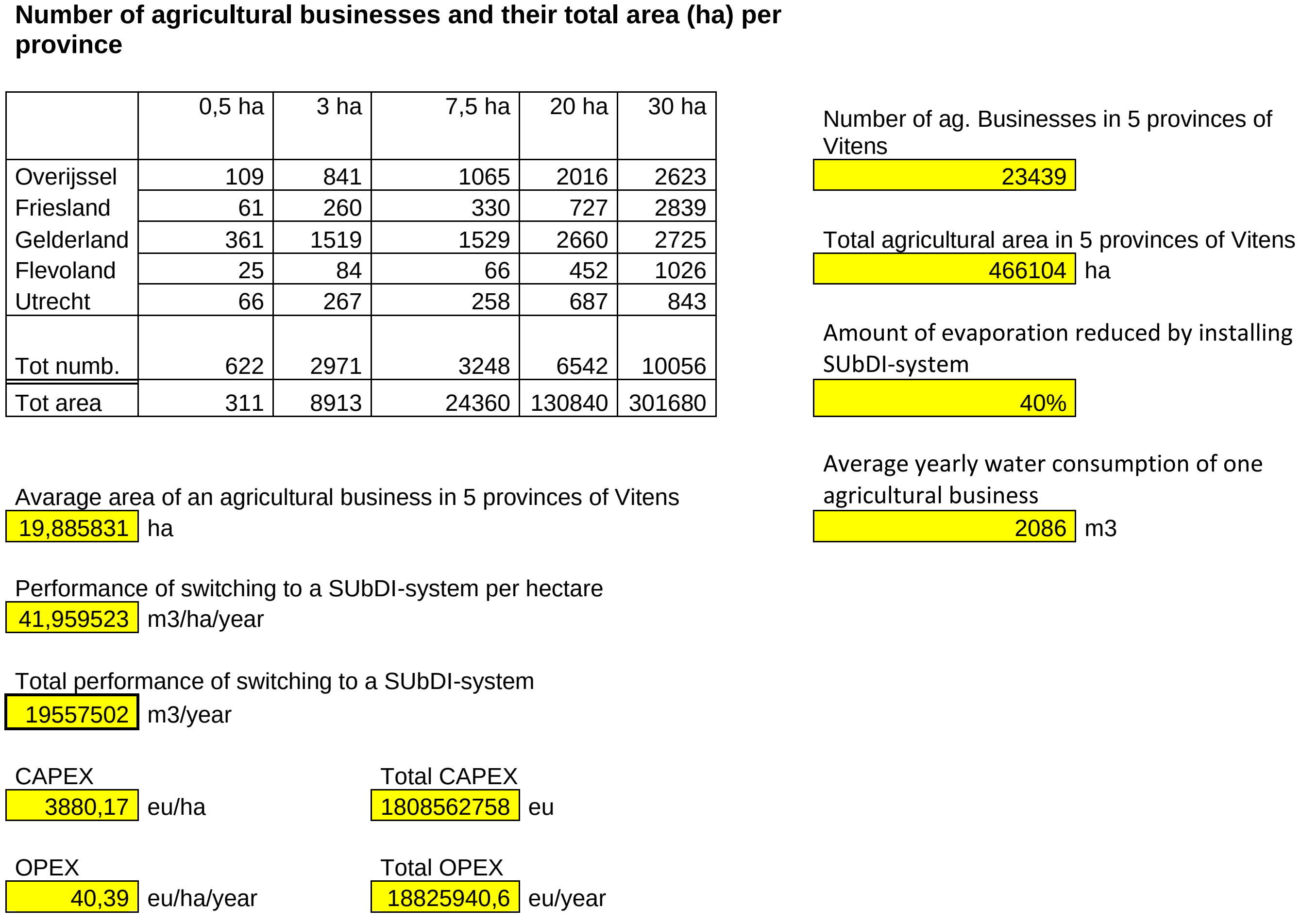
1. **Terracing**: this method can be used in sloping areas by developing different horizontal terraces that slow runoff down and allow for more infiltration (Wei *et al.*, 2016).
2. **Contour barriers** increase surface roughness of a slope. This gives water that is flowing over the surface more time to infiltrate. Possible barriers can be vegetative like grass strips or non-vegetative made of rock (Stevens *et al.*, 2009)
3. **Contour trenching** includes small trenches dug perpendicular to the slope of an area to collect runoff and give it more time to infiltrate (Ali *et al.*, 2017).
4. **Contour farming** includes multiple farming practices like tillage and planting perpendicular on a slope. This also increases surface roughness (Farahani *et al.*, 2016).
5. In a **micro catchment**, water is transported downslope towards a small infiltration basin. In this basin trees are planted that can store the excess water in their rootzone (Boers *et al.*, 1986)
6. The **tied ridging** method describes a sloping field in which rectangular basins are used to collect rainwater and give it more time to infiltrate (Mesfin *et al.*, 2010).
7. Farm **storage ponds** are larger basins than described in method 6. Here larger ponds are used to store excess rainwater and reuse it later as irrigation water during drier periods (Ngigi, 2005).
8. A **percolation pond** collects excess rainwater that cannot infiltrate due to impermeable surfaces which can often been found in cities (roofs, pavements, roads) or compacted agricultural soils. The water is stored in such ponds and gets time to percolate towards the water table of the water bearing aquifer (Wadhwa & Kummamura, 2021). A similar method that is successfully applied in the Dutch cities Enschede and Utrecht are **wadis**. These wadis also collect excess rainwater and gives it more time to infiltrate in the soil, this increases the amount of groundwater and reduces the amount of excess rainwater on the streets (Hofman and Paalman, 2014).

9. (Subsurface) **drip irrigation** reduces the amount of runoff on a land surface, since lower amounts of water are applied at once. The water that is applied is used more efficiently by the plant (Lamm, 2002).

Evaporation reducing methods:

1. The use of **cover crops**. These can be grown to provide ground coverage especially during summer to reduce evaporation. When these crops start to take up too much water and nutrients that are applied for the yielding crop, the cover crop can be killed and left behind as a ground covering mulch (Ward *et al.*, 2012).
2. Mulching can reduce the evaporation rate on a soil. Impervious plastics reduce the evaporation rate strongly, but also stop rainwater infiltration. Porous mulching allows for more rainwater infiltration but reduces evaporation rates less than plastic films (Zribi *et al.*, 2015).
3. (Subsurface) **drip irrigation** also reduces the amount of evaporation, since water is used more efficiently and can infiltrate faster into the root zone of crops (Lamm, 2002).

APPENDIX III - AGRICULTURAL DATA AND CALCULATIONS



Number of agricultural businesses and their total area (ha) per province

	0,5 ha	3 ha	7,5 ha	20 ha	30 ha
Overijssel	109	841	1065	2016	2623
Friesland	61	260	330	727	2839
Gelderland	361	1519	1529	2660	2725
Flevoland	25	84	66	452	1026
Utrecht	66	267	258	687	843
Tot numb.	622	2971	3248	6542	10056
Tot area	311	8913	24360	130840	301680

Number of ag. Businesses in 5 provinces of Vitens
23439

Total agricultural area in 5 provinces of Vitens
466104 ha

Amount of evaporation reduced by installing SUbDI-system
40%

Average yearly water consumption of one agricultural business
2086 m3

Avarage area of an agricultural business in 5 provinces of Vitens
19,885831 ha

Performance of switching to a SUbDI-system per hectare
41,959523 m3/ha/year

Total performance of switching to a SUbDI-system
19557502 m3/year

CAPEX
3880,17 eu/ha

Total CAPEX
1808562758 eu

OPEX
40,39 eu/ha/year

Total OPEX
18825940,6 eu/year

Sources: Rijksoverheid, (2019)
Wageningen Economic Research
Valentín *et al.*, (2020)
Jacques *et al.*, (2018)

APPENDIX IV ADDITIONAL SOLUTIONS

Solution	Internal/External	Description
Developing a network of extraction location regionally	Internal	Alternation between different extraction location can reduce the lowering of the groundwater table in an area, which can result in a reduction of the impact on the environment caused by (shallow) groundwater extraction
Closure of discharge channels	External	Closure of small channels that discharge water from an (nature) area can result in an increase in the buffering capacity of a specific area. This has already been done as a pilot close to Doetinchem by *Staatsbosbeheer*. A possible risk is a higher change of flooding.
Collecting rainwater (rural water buffer)	Internal/External	Rainwater can be collected in a rural environment and used as a source of drinking water during drier periods. This can be done by Vitens itself on a larger scale, or by the customers of Vitens, to reduce the demand for fresh (drinking) water.
Separating drinking water from other water (showering, toilet use, gardening)	Internal	Water with different qualities can be delivered to the customer. This increases the flexibility within water quality. It is for example not necessary to water your plants with water with drinking water quality. This solution might be expensive, due to the necessity for different quality infrastructures.
Early warning monitoring system	Internal	An early warning monitoring system can warn when low quality water is identified upstream in the river of a riverbank filtration extraction location. Other solutions can be used when this is observed to reduce the impact of this possible contamination. The same can be applied at shallow rural groundwater extractions, but this is less useful, because travel times of contaminants in the subsurface are relatively low and there is a relatively long period to adapt to these contaminations.
Alternative source (seawater or Ijsselmeerwater)	External	This (salt/brackish) water can be a solution to solve quantity problems. As described in the results section, filtration of salt or brackish water requires an expensive filtration system, which also has relatively high operational costs. This solution is advised to only be used during severe drought events, when no groundwater can be extracted due to the impact on nature. This solution also makes the DSE solution less relevant, because if salt water is extracted from surface water, why should you also extract it from a deep aquifer? This only results in additional costs. The DSE solution is for this reason only useful when salt concentrations are low in groundwater compared to surface waters.
Urban water buffer	External	Detailed description in *Appendix V*.

Small scale urban water buffer (rooftop collection)	Internal	Rainwater can also be stored on smaller scale per household, which can later be used for lower quality purposes (washing, gardening) or even been filtered for drinking water purposes
Flexibility by versatility (regional)	Internal	Alternating between deep and shallow extraction is a form of flexibility by versatility. Flexibility by versatility can be generated by multiple methods on different scales (regional or national) by combining different methods to gain water for drinking water production.
Creating awareness of the value of water	Internal	When the customers of Vitens are more aware of the value (and sometimes scarcity) of fresh water, they might be willing to reduce their water consumption. This awareness can be created by educating children in schools at a young age or starting a campaign to create awareness in adult groups.
Circularity	Internal	When all the sewage water from the customers of Vitens is filtered and reused for drinking water production purposes, the dependence of Vitens on groundwater extraction will be strongly reduced. This only requires small scale extraction of groundwater (or another source) to compensate for evaporation (= loss from the cycle). Capital expenditures are considered to be high, since filtration systems have to be installed and infrastructures need to be expanded.
Reinwaterkelders	Internal/External	Another method to store fresh water in the subsurface from periods with a high availability for periods with a low availability.

APPENDIX V URBAN WATER BUFFER

QUANTITY – EXTERNAL – STORYLINE 1, 2, 3 AND 4

In urban areas, infiltration of rainwaters is often blocked by impermeable land coverage like: tiles, asphalt or buildings. Rainwater flows over these surfaces towards lower elevated areas and might result in flooding of these areas during severe rainfall events.

This problem can also been seen as a possibility to collect this excess rainwater and cooperate with the municipalities that are struggling with discharging this water. This concept of collecting excess water in urban areas is called the *Urban Waterbuffer* (UWB). Buffering of this water occurs in several pilots in the Netherlands. Two of these pilots are:

1. The neighbourhood Spangen in Rotterdam, where excessive rainwater that falls on the field of the Sparta Stadium and the surrounding area (40.000 m^2) is collected, filtered and eventually stored in an aquifer. In drier periods this stored water can be used to water the grass in the stadium (Zuurbier & van Dooren, 2019).
2. The Lentsesteeg in Rheden is a street that has (for Dutch standards) a steep slope. Rainwater from the Veluwe flows via this road down to the village. To reduce the impact of flooding events the infiltration capacity is increased by installing infiltration sources. This water is stored in the underground and has a large buffering capacity, since the water table is around 4 meters below the surface (Zuurbier & Dekker, 2020).

Performance:

Rotterdam: The project saves a total of 15.000 m^3 of drinking water by reusing rainwater. The quality of the water is too low to use it as drinking water. Contaminants are: iron, calcium, manganese and zinc. These are partly filtered out by the biofilter, but extra filtration steps are required to use this water as drinking water.

Costs:

Rotterdam: In total 1.2 million euros was invested to install the UWB in Spangen. 68% of this investment is used to make a temporary buffer in the subsurface. This is necessary because the biofilter and infiltration in the aquifer have a lower filtration and infiltration rate than precipitation is collected. This temporary buffer costs around 800 thousand euros. It is expected that the maintenance costs are around 12 thousand euros per year (€480k in 40 years). The companies involved in this project claim that the UWB is a good alternative for supplying drinking water. When benefits like: reduced pressure on the current sewer system, no need for importation of drinking water from regular production companies, special improvement of the neighbourhood and CO_2 reduction are subtracted from the previously mentioned costs, one cubic meter of water from the UWB will cost €0,49.

In Rheden, an investment of 41 thousand euros was required to install the infiltration sources and filters for this type of UWB. It is not possible to express a price for 1 cubic meter of water since data for buffering capacity is missing.

A summary of this UWB solution is visible on the next page.

Solution	Main class	Subclass	Storylines				Performance	Costs	Risks	Missing data
Name	**Quality/ Quantity**	**Internal/ External**	**1**	**2**	**3**	**4**		**CAPEX/OPEX**		
UWB	Quantity	External	x	x	x	x	**15.000 m^3 $year^{-1}$**	**€1.200.000/ €12.000 $year^{-1}$**	1. Vandalism (yearly probability) 2. Contamination of the underground due to infiltration of buffered water with another quality 3. Failing pipes 4. first flush (yearly) contamination (PAKs and pesticides in Rheden) 5. Clogging (yearly) 6. legionella in summer (yearly) 7. Collected water has a low quality	1. Buffering capacities of soils 2. Quantification of the many risks