Aquifer Storage and Recovery (ASR)

*Design and operational experiences for water storage through wells*
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Preface

This document presents the opportunities that Aquifer storage and recovery (ASR) projects may provide in urban, agricultural and industrial areas and is intended to be used by urban water utilities (such as drinking water companies), horticulture, industries and municipalities. At an introductory level, this document summarizes the relevant information needed to consider ASR projects. It introduces different ASR applications and two varieties on the ASR concept (ASTR and ATR). In addition, it presents showcases to illustrate the diversity of methods that can be used. The report is built upon (scientific) literature and operational experiences in the United States, the Netherlands and Australia.
Summary

Due to increasing climate variability and urbanization Europe is challenged with obtaining a sustainable long term supply of fresh water. Larger fluctuations in river discharge and salt water intrusion as a result of sea level rise have a direct negative impact on the availability of fresh water for drinking water supply and agriculture. At the same time larger seasonal variations in precipitation result in an increased demand for fresh water during dry months. To ensure the sustainable and sufficient supply of fresh water, an adequate and sustainable adaptation strategy is required.

Temporal storage of water can help overcome this mismatch in water supply and demand in time, allowing seasonally variable sources of water to be used as reliable water supply. Therefore, one of the main concerns for the coming decades is the provision of sufficient storage capacity to enhance the buffer capacity of water supply systems. Aquifer storage and recovery (ASR) is often cost–effective in comparison to aboveground alternatives that require the construction of water treatment plants and surface reservoirs. In addition, there may be insufficient space or desire for aboveground water storage, such as in urban areas. In these cases, aquifer storage of water provides an attractive alternative to increase storage capacity, as it results in a relatively very small footprint aboveground.

ASR through wells is a specific type of technology for the infiltration of water into aquifers, more generally known as managed aquifer recharge (MAR). Recent technical advances and operational experiences have demonstrated that the use of wells during ASR is a feasible and cost-effective method for recharging aquifers, as confirmed by research pilots and operational plants worldwide. Several relatively recent ASR concepts include aquifer storage transfer and recovery (ASTR) and aquifer transfer recovery allow ASR to be applied for a wider number of purposes under a wider range of conditions. The development of these new techniques has led to improved ASR recoveries, satisfying water demands. Recent developments in ASR techniques and applications demonstrate that ASR is feasible in aquifers with very different settings, including conditions that were previously deemed unsuitable. For example, ASR can be applied in very thin aquifers and unconfined aquifers using horizontal wells. and in brackish/saline aquifers using ‘Multiple Partially Penetrating Wells’ (MPPWs) or separate wells that extract saline groundwater (Freshkeeper and Freshmaker concepts).

Careful planning and design are essential to develop a successful ASR set-up. Water availability, water demand and source water characteristics guide the initial design and type of the ASR system to be constructed. The evaluation of both hydrogeological aquifer properties and operational parameters is essential to determine ASR feasibility and design criteria.

Future research and pilot projects are expected to increase application and optimization of ASR. New developments will likely further enhance the number of aquifer and water types suitable for ASR. Dissemination of knowledge of existing and upcoming projects is required to facilitate project development and risk assessment for new projects.
1 Introduction

Due to increasing climate variability and urbanization Europe is challenged with obtaining a sustainable long term supply of fresh water. Larger fluctuations in river discharge and salt water intrusion as a result of sea level rise, land subsidence and a decrease in summer discharge by major rivers, have a direct negative impact on the availability of fresh water for drinking water supply and agriculture. At the same, prolonged droughts and increased temperatures may result in an increased demand for fresh water (e.g., Intergovernmental Panel on Climate Change (IPCC) 2007; Schröter et al. 2005), resulting in a nett shortage of freshwater, even if yearly mean gross precipitation tends to increase in some parts of Europe (KNMI 2008). An adequate and sustainable adaptation strategy is required to ensure the sustainable and sufficient supply of fresh water (European Environment Agency, 2012). Temporal storage of water can help overcome the mismatch in water supply and demand in time, allowing seasonally variable sources of water to be used as reliable water supply. One of the main concerns for the coming decades is, however, the storage capacity of water supply systems.

Storage of water: surface storage versus aquifer storage
Substantial amounts of water can either be stored aboveground or underground in aquifers (aquifer storage). Surface storage in rivers, lakes or ponds is widely applied and represents the majority of the installed global storage capacity. Obviously, the amount of water that can be stored at the surface depends on the dimensions of the basin, whereas subsurface storage capacity is widely available. Therefore, aquifer storage is often cost-effective as compared to aboveground alternatives that require the construction of water treatment plants and surface reservoirs. In addition, there may be insufficient space or desire for aboveground water storage, for instance in urban areas. In these cases, aquifer storage provides an attractive alternative to increase storage capacity, as it requires only a small footprint aboveground.

Aquifer storage and recovery through wells
The use of wells for aquifer storage and recovery (ASR, Figure 1) is a specific approach for the infiltration of water into aquifers, which is more generally known as managed aquifer recharge (MAR). While most aquifer recharge still occurs through surface facilities like ponds and river channels, an increasing amount of recharge occurs through wells. Recent technical advances and operational experiences have demonstrated that ASR is a feasible and cost effective method to recharge natural aquifers (Pyne, 2005; Maliva and Missimer 2010). In this comprehensive guide the current knowledge on ASR, as gained from research and operational experiences, is collated. This overview is presenting the opportunities that ASR projects may provide in urban areas, summarizing at an introductory level the relevant information needed when considering an ASR project, introducing different concepts of ASR and presenting showcases to illustrate the diversity of methods that can be used for ASR. It is intended to be used by urban water
utilities (such as drinking water companies), horticulture, industries and municipalities.

Figure 1: Example of an ASR application in Dutch Greenhouse areas. A surplus of fresh roof water is injected and stored in a deeper confined aquifer. From this ASR bubble, freshwater can be recovered in time of shortage.

Reading guide
In Chapter 2 different reasons for implementing an ASR system are highlighted and different concepts of ASR are introduced. Subsequently the relevant information needed to design an ASR system is summarized in Chapter 3 at an introductory level, taking into account factors such as water availability and demand, aquifer characteristics, costs and environmental effects. To illustrate the diversity of methods that can be used for ASR, the operational experiences are discussed and different showcases are presented in Chapter 4. A short summary of the most important facts and suggestions for dissemination of knowledge and ideas about expected developments and possible future uses of ASR are presented in Chapter 5.
2 Aquifer storage and recovery: concepts and functions

2.1 What is ASR?
In this document, aquifer storage and recovery (ASR) is defined as the storage of water in a suitable aquifer through a well and the recovery of water using the same well when needed to meet the demand of urban, agricultural, ecosystem, industrial, recreational, emergency and other water uses. The fundamental objective of an ASR system is to recover a high percentage of injected water (i.e. to maximize the recovery efficiency) at a quality that is (nearly) ready to be put to beneficial use.

Recent technical advances and operational experiences have increased ASR performance, demonstrating that ASR is a feasible and cost-effective method for freshwater supply.

2.2 Reasons to implement an ASR system
While there are numerous different reasons for implementing an ASR system, most ASR applications are for seasonal and long-term, emergency storage of water. Another common application of ASR is for improving the water quality of the stored water. The most common reasons for implementing an ASR are discussed below:

1. Securing and increasing water supplies:
Enhancing groundwater recharge and storage via ASR provides an important potential source of water for urban and rural areas. We can distinguish three types of storage:
- Emergency storage: The storage of water when available to provide an emergency supply to meet demands when the primary source of water is unavailable, due to accidental loss, contamination, a natural disaster, maintenance activities or other unforeseen circumstances.
- Seasonal storage (or peak storage): This is the storage of water during the wet season, when water is available or when water quality is good, and recovery during the following dry season or other months when water is needed.
- Long term storage (or water banking): Water banking is the long term storage during wet years or when distribution facilities have spare capacity, and recovery years later during extended droughts or when facilities are inadequate to meet system demands.

2. Improving the quality of the stored water:
Water treatment capabilities of aquifers are substantial, particularly for pathogen removal and reduction of the concentrations of disinfection by-product (DBP’s). ASR systems can therefore provide an inexpensive method for meeting water quality standards.
Other less common reasons for implementing aquifer recharge are:

- Improving groundwater quality,
- Preventing salt water from intruding into coastal aquifers,
- Management of undesired water (i.e. the reuse of effluents),
- Impeding land subsidence or to maintain or restore groundwater levels,
- Reducing evaporation losses of stored water.

2.3 **ASR types using wells**

Internationally there is a large and growing number of ASR application types, using different types of well construction, target aquifers and water sources to be stored. In this document a distinction is made between ASR sensu stricto, and two varieties of this concept (based on Stuyfzand et al., 2012, Figure 2):

- **Aquifer storage and recovery (ASR):** ASR is the ‘storage of water in an aquifer through a well when water is available, and the recovery by the same well during water demand’ (Pyne, 2005). The periods of infiltration, storage and recovery are hereby typically separated. This type of system is preferred when storage is the primary objective.

- **Aquifer storage transfer and recovery (ASTR):** ASTR is a system of separate infiltration and extraction wells (“single purpose wells”), with recovery immediately after or some time after infiltration is stopped. The infiltration and recovery rates may differ (Stuyfzand et al., 2012). This type of system is preferred at sites where an ASR well will experience problems with bubble drift as a result of regional flow. Two separate wells for injection and recovery can also be preferred when a partly continuous supply is required. Also, the use of separate wells may be desirable to improve stored water quality by providing additional residence time and to take advantage of self-purification during transport in the aquifer.

- **Aquifer transfer and recovery (ATR):** ATR is a system of separate infiltration and abstraction wells (‘single purpose wells’), with simultaneous infiltration and recovery in which the infiltration and recovery rates may differ. This type of system is used when a continuous water supply is needed and soil passage contributes to water quality improvements (Stuyfzand et al., 2012).
Figure 2 Schematic of the difference between ASR, ASTR and ATR in three aquifers located underneath each other; 1=Injection, 2=storage and 3=recovery during ASR cycle 1, without regional flow, 4,5,6 = ditto during ASR cycle 2 with expanded bubble; A, B, C = resp. injection, storage and recovery during an ASTR cycle, with strong regional flow (From Stuyfzand et al., 2012).
3 Design of ASR systems

There are many different factors that have to be taken into account when designing an ASR system. At an introductory level, this chapter summarizes the relevant elements that need to be taken into account to determine the feasibility of an ASR project.

3.1 Defining recharge objectives
The design of an ASR system is initially driven by the objective of the system. Therefore, the first step in designing an ASR system is to define the recharge objectives (see paragraph 2.2 for recharge objectives). If there are multiple objectives a distinction must be made between the primary objective of the system and one or more secondary objectives. Although this may seem obvious, it is important to carefully consider the different recharge objectives and prioritize them because they largely dictate the requirements of the target aquifer and water source.

3.2 Water demand, availability and storage requirement
In addition to the recharge objective(s), the design of an ASR system is driven by the water demand and the availability of source water. These aspects together define the storage requirement.

Water demand
Sufficient demand for the recovered water is a prerequisite for a successful ASR system. One of the first steps in an ASR feasibility study is therefore to evaluate the current and projected water demand. Ideally, daily water demand data over a period of 10-15 years should be analyzed, including averages, monthly variability, observed trends and expectations. These data give insight into the volume of water required for recovery to meet system demands and gives insights into the amount of idle supply, treatment and transmission capacity required.

Water source for storage
For an ASR system to be feasible excess water needs to be available for storage. Water from various sources, such as storm water, river water, reclaimed water, mains water, desalinated seawater, rainwater or even groundwater from other aquifers can be used for storage. For each potential source water quantity, quality and associated variability should be carefully evaluated in order to assess the suitability for ASR application. Similar to the water demand, daily water supply data over a period of 10-15 years should be analyzed, including average, monthly variability and trends, particularly for temporally variable sources. Once recharge quality and quantity issues have been addresses, it is possible to evaluate those times of the year when recharge water is available in a useful quantity and with suitable quality.

Storage requirement
Based upon the variability in water demand, water supply and water quality the amount of water that needs to be stored can be estimated (see example in
Figure 3). Subsequently the rate at which the water must be recharged and recovered during an operational cycle can be estimated. ASR systems are sized with respect to injection and recovery rates and total recoverable volume during an operational cycle; using the total recoverable volume and rate of recharge and recovery the capacity of individual wells and the required number of wells can be determined.

3.3 Hydrogeology

All ASR projects require a thorough characterization of the hydrogeological conditions in the vicinity of the project site. Careful evaluation of the hydrogeology is required because the recovery efficiency (see paragraph 2.1 for recovery efficiency) is dependent on the specific hydrogeology at the site. Some of the main aquifer characteristics that should be assessed are:

- lithology and structural elements (fractures, bedding, joints),
- thickness, depth and extent of the aquifer,
- thickness, depth and extent of surrounding aquitards (if any),
- water quality in the target aquifer,
- geochemical composition (reactivity) of the aquifer matrix,
- salinity and water quality of ambient groundwater, and
- regional groundwater flow.

The goal of this investigation is to identify positive attributes of the underground, such as zones with high porosity and permeability that would be favorable for a particular recharge method, as well as negative attributes.
such as the presence of impermeable layers or the presence of contaminants. The thickness, depth and extent of the target aquifer must be analyzed to assess if there is sufficient storage space. The salinity of the native water should be determined as the recovery efficiency of the system can be affected by upward bubble drift or mixing between the infiltrate and native saline groundwater. Upward bubble drift is the phenomenon in which density differences between saline and fresh water cause the lighter freshwater to float up (Figure 4). This may increase the risk of premature saline water extraction during recovery. Mixing between the infiltrate en native saline groundwater may result that water quality threshold values be exceeded, reducing the total amount of water that can be recovered. Regional groundwater flow should be analyzed because it can result in unacceptable movement of infiltrated water as a result of lateral bubble drift (Figure 4) when using a single-well ASR system and other. Other ASR types may be considered to deal with regional groundwater flow effects (see paragraph 2.3 for varieties on the ASR concept).

3.4 Selection of an ASR concept and preliminary design

The selection of a suitable ASR system follows after determining the ASR aspects discussed in the previous paragraphs:

- the recharge objectives
• the water demand
• availability and storage requirement
• selection of a suitable aquifer.

As briefly discussed in Paragraph 2.3 there are various ASR types. Choosing the appropriate type is not always straight-forward. The main considerations in choosing a concept include:

• The objectives of the ASR system;
• The presence or absence of a regional groundwater flow.

A simplified schematic for selecting an appropriate ASR system is given below, based on these main considerations (Figure 5).

After selection of an ASR system a preliminary design can be set up, which contains a layout of the facilities and controls. There are many choices for the design of an ASR facility. A design might consist of shallow or deep infiltration wells, vertical or horizontal wells, wells that can both inject and recover water, or a combination thereof. Also, pre- and post treatment facilities and monitoring wells may have to be incorporated in the design.

To guide the project design through the next project phases several aspects should be clearly defined during the preliminary design phase, such as:

• the structure of the recharge-recovery cycles
• the period for which water is stored before it is recovered
• how to meet the quality criteria for the recovered water, or in other words, when to stop recovery as based on on-line quality monitoring.

Figure 5 Simplified diagram for the selection of a suitable ASR system
3.5 Financial feasibility
One of the main criteria to consider ASR a valid option, is whether it provides water storage at lower costs than other storage options. The financial feasibility of an ASR system is dependent on the total costs of the system, the available volume for storage and the recovery efficiency of the ASR plant. There is no universal recovery efficiency standard for a successful ASR system. If modest recovery efficiency still provides the needed water at a competitive price the system can still be a success.

3.6 Environmental feasibility
The construction of an ASR system could result in negative environmental effects such as undesired changes in groundwater level in the surroundings of the system or undesired changes in the salt-fresh water interface, or even undesired water quality changes (for instance arsenic). Prior to construction an impact assessment should be performed in order to quantify these effects and to determine if additional measures should be taken to mitigate these effects. An environmental impact assessment is often required in order to be granted an operational permit.
4 Operational experiences

There is a large number of ASR schemes operational world-wide with a growing variety of types. In Chapter 2 the different ASR types (ASR, ASTR and ATR) were already introduced. In Chapter 4 the operational experiences with these different ASR systems are presented and discussed. For each ASR type different showcases are presented, as summarized in Table 1, to illustrate the diversity of methods, source waters, hydrogeological settings and end-uses of recovered water. For each concept, the main applications and technical and operational issues are discussed.

Table 1 Overview of showcases presented in Chapter 4

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4.1 Aquifer Storage and Recovery (ASR)

As introduced in Chapter 2, Aquifer Storage and Recovery (ASR) is defined as the ‘storage of water in an aquifer through a well when water is available, and the recovery by the same well during water demand’ (Pyne, 2005). Because wells are used for both infiltration and withdrawal they are referred to as ‘dual purpose wells’.

How does it work?

Water is injected into an aquifer during wet periods, during periods of low demand or when water quality is good. The injected water displaces the naturally present water in the aquifer occupying a volume around the well (Figure 6). Water is usually recovered during times of high water demand. The periods of infiltration, storage and recovery are thus typically separated.
Applications of ASR
Operational ASR systems are widely applied including countries such as USA, Spain, Australia and the Netherlands. Most operational ASR systems are for long-term or seasonal storage of water (Showcase 1 & 2). However an increasing number of water managers is constructing ASR systems to ensure reliability of supply during emergencies such as floods, contamination incidents, pipeline breaks or to ensure supply during periods of maintenance. Because of the wide range in applications there is also a wide range in size for different ASR systems. ASR systems reported in literature range in scale from single well systems for domestic or horticultural irrigation to ASR well fields consisting of over 20 wells to meet water demand for urban areas or industrial use (Showcase 4). Typical storage volumes for individual wells can hereby range from 0.04 Mm$^3$ for a small ASR plant to 2 Mm$^3$ for a large plant (Pyne, 2005). The largest ASR well fields in operation have design storage volumes in excess of 4 Mm$^3$, enabling a seasonal water supply of 30 to 280 ML/d (Pyne, 2005).

Design issues
A fundamental objective of an ASR system is to recover a high percentage of injected water at a quality that is ready to be put to beneficial use, i.e. to maximize the recovery efficiency. The recovery efficiency of an ASR well is dependent on the specific hydrogeology at the site and benefits from a low or absent groundwater flow and low groundwater salinity. A low regional groundwater flow prevents lateral bubble drift (Figure 4). The salinity of the native water also impacts on the recovery efficiency of the system. Density differences between saline and fresh water cause the lighter freshwater to float up (upward bubble drift, Figure 4) increasing the risk of saline water extraction during recovery. To maximize the recovery efficiency in situations with upward bubble drift a technique has been developed which allows for infiltration and extraction at different depth levels; the Multiple Partially Penetrating Well (Showcase 2). Additionally, mixing between the infiltrate

![Figure 6 Schematic representation of a basic ASR well (Pyne, 2005)]
and native saline groundwater may result in exceedance of the water quality threshold values, reducing the total amount of water that can be recovered. To maximize the recovery efficiency in brackish or saline aquifers different techniques have been developed, such as the Freshmaker concept (Showcase 3). These techniques enable the expansion of (thin) freshwater lenses in unconfined brackish or saline aquifers by combining artificial recharge with interception of the underlying brackish water. The Freshmaker concept is based on the Freshkeeper concept which prevents salinization of abstraction wells by stabilizing the fresh-water interface through simultaneous abstraction of the upper fresh and lower brackish groundwater (Appendix II). The Freshmaker concept also allows for storage of fresh water in saline unconfined aquifers. Most experience with ASR to date is with semi-confined and confined aquifers in which the naturally present groundwater is displaced in a lateral direction. Storage in unconfined aquifers can also be feasible, but can be negatively impacted when the build-up of a mound in the water table intersects either the ground surface or local drainage systems, causing loss of the stored water due to surface drainage (Pyne, 2005). By combining infiltration with extraction of native saline groundwater the Freshmaker concept prevents the build-up of a groundwater mound.

**Operational issues**
One of the main problems in the operation of ASR systems is a decrease in the capacity of the wells as a result of well clogging, especially when the infiltration water contains significant concentrations of total suspended solids in combination with a fine grained clastic aquifer. ASR wells are much less susceptible to clogging than ATR and ASTR wells thanks to flow reversal. Well clogging can be prevented by pretreatment of the infiltration water or by frequent backflushing. A clogged well can be rehabilitated by physical scrubbing, acidification, jetting and purging (Olsthoorn, 1982).

In addition, problems related to adverse changes in water quality in the target aquifer are possible, which would necessitate post-treatment of the recovered water and thereby make ASR less cost-effective. For example, a Mn-increase in recovered water of an ASR pilot in the Province of Limburg above the drinking water standard of 0.05 mg/L was one of the reasons to skip ASR as a viable option for optimizing drinking water supply (Antoniou et al. 2012).

**4.2 Aquifer Storage Transfer Recovery (ASTR)**
As introduced in Chapter 2, Aquifer Storage Transfer Recovery (ASTR) is a system of separate infiltration and extraction wells ("single purpose wells"), with recovery immediately or some time after infiltration is stopped. The flow rate of infiltration and recovery may differ (Stuyfzand et al., 2012).

**How does it work?**
Water is injected into an aquifer using an injection well during wet periods, during periods of low demand or when water quality is good. The injected water displaces the naturally present water in the aquifer establishing a volume around the well (Figure 10). Water is recovered immediately after or...
some time after infiltration is stopped using a recovery well. The periods of infiltration, storage and recovery can thus be separate or simultaneous.

**Showcase 1:**

The Peace River ASR well field, Florida, United States (based on Eckman et al., 2004)

In the Southeast, Southwest and Western states of the United States ASR has become a prevalent tool for providing a reliable supply of water throughout the year. The Peace River ASR well field is comprised of 21 ASR wells (in 2004) with a combined capacity of 68 ML/day. It was built as an expansion of the Peace River Regional Water Supply Facility. The principal objective of the ASR system is to provide seasonal storage. Long term storage is a secondary objective.

The water supply facility relies on surface water from the Peace River, a variable water source with flows ranging from billions of liters per day to periods of almost no flow. During a period of approximately 9 months raw water from the Peace River is pumped to a 2.5 billion-liter, off-stream, raw-water reservoir (Figure 7). Raw water is subsequently pumped to the water-treatment plant, where it is treated using a conventional coagulation process. Following treatment, the water is pumped to clear-water storage. From the clear water storage water is delivered to meet supply contracts. The surplus treated water remaining after delivery of contract water is injected into the ASR wells. The ASR wells are designed for injection and recovery rates of about 3,8 ML/day per well. In the periods when the facility is unable to divert enough water from the river to meet supply contracts, water is recovered from the same wells and used for delivery.

![Figure 7 Peace River Water Supply Facility layout (Eckman et al., 2004)](image)
Showcase 2:

ASR in a brackish aquifer for irrigation water supply, Nootdorp, the Netherlands

In November 2011 a new type of small-scale ASR installation for irrigation supply was installed at Nootdorp, the Netherlands. In this system roofwater from a greenhouse is collected and stored in a brackish aquifer. To prevent recovery of brackish water as a result of buoyancy effects in the denser brackish groundwater, 'Multiple Partially Penetrating Wells' (MPPW) are used.

How does it work?

Greenhouse roofwater is collected in a small tank, able to store 20 mm of precipitation. When the water in this storage tank reaches a maximum set level, the water is first treated by slow and rapid sand filtration. Subsequently the water is pumped into a 3 m high PVC stand pipe which provides the pressure required to inject the water into the target aquifer with a flow rate of 10-15 m$^3$/h. Recovery starts when the water level in the irrigation water tank drops beneath a minimum set level. In order to prevent recovery of brackish water due to buoyancy effects or seepage and to increase the recovery efficiency, water is infiltrated and recovered using a 'Multiple Partially Penetrating Well' (MPPW). This MPPW consists of four risers with screens at different depths. This allows for injection and recovery at different depths. After an initial injection and recovery phase using all well screens, fresh water is primarily injected deep into the aquifer, while recovery takes place at the aquifer’s top.

Figure 8 Principle of MPPW: injection takes place in all 4 wells but at a higher rate at the bottom of the aquifer, whereas recovery takes place only in the upper part of the aquifer (Zuurbier et al., 2012).
Show case 3:

Freshmaker field pilot in Ovezande (Zuid-Beverland, the Netherlands)

ASR in brackish and saline aquifers often experiences problems as a result of buoyancy effects and mixing with brackish and saline groundwater. The Freshmaker concept increases small natural fresh groundwater lenses by combining the interception of underlying saltwater using horizontal abstraction drains or wells, with artificial recharge of fresh water. The horizontal drains make the technique feasible in thin aquifers, which is a prerequisite in many of the world’s delta areas.

In March 2013 the ‘Freshmaker consortium’ consisting of Meeuwse Goes, KWR Watercycle Research Institute and ZLTO started the first field pilot for aquifer storage using the Freshmaker concept in Ovezande, the Netherlands. Using this technique it is aimed to store a significant volume of freshwater in the subsurface (5,000 to 8,000 m$^3$) for irrigation supply.

In Ovezande freshwater is taken from a watercourse during the winter period and infiltrated into the aquifer using a horizontal drain at 7 m below surface. To prevent upward bubble drift, the saltwater underlying the freshwater lens is intercepted at approximately 16 m depth using a second horizontal drain. The extracted saltwater is discharged to brackish surface water, at sufficient distance from the freshwater intake. During the following dry season the freshwater is recovered making extra water available for crop irrigation.

Figure 9 Schematic side view of the Freshmaker concept
Applications of ASTR
ASTR system can be used for the same applications as ASR (e.g. seasonal, long-term or emergency storage, for the reuse of effluents). However, the use of separate wells for injection and recovery in ASTR may improve the system performances (i.e. greater recovery efficiencies). Better system performances can for instance be obtained at sites where an ASR well will experience problems with bubble drift as a result of regional flow (for an explanation on bubble drift see Fig.4). Two separate wells for injection and recovery can also be preferred when a (partly) continuous supply is required. Additionally the use of separate wells may be desirable to improve stored water quality by providing additional residence time and to take advantage of an aquifer’s natural self-purification.

Design issues
The success of an installed ASTR system is mainly dependent on the aquifer characteristics and the water quality of the infiltration water. Both operational experiences and research show that the elimination of pathogenic microorganisms through natural filtering by the aquifer requires a certain transport distance and residence time in the aquifer. Hydrological calculations should be made to provide insight in the travel times of infiltrating water.
When fresh water is infiltrated into a brackish or saline aquifer the density differences between saline and fresh water causes the lighter freshwater to float up (upward bubble drift, see Figure 4). In an ASR system this can lead to a decreased recovery efficiency. In such situations the recovery efficiency of an ASTR system can be maximized by injecting and extracting fresh water at different depths in the aquifer.

Operational issues
One of the main challenges in the operation of ASTR systems is a decrease in the capacity of the wells as a result of well clogging. Well clogging can be prevented by pretreatment of the infiltration water or by frequent backflushing. A clogged well can be rehabilitated by physical scrubbing, acidification, jetting and purging (Olsthoorn, 1982).
Show case 4

**ASTR for water treatment (combined with reed-bed filtration), a project by CSIRO in Salisbury, Australia** (based on Page et al., 2010, Chapter 8)

Construction of the Aquifer Storage, Transfer and Recovery (ASTR) system in Salisbury started in 2005 and was completed in 2008. The ASTR project was developed to gain understanding of the recoverability of recharged water and the water quality improvements of harvested, injected and recovered storm water in order to develop management strategies for reliable, sustainable production of water of potable quality sourced from storm water.

The storm water harvesting system consists of a weir which diverts water into an in-stream basin which serves as an initial settling basin for the storm water (see Figure 11). From the in-stream basin, water is pumped at 3 ML/hour to the 48 ML holding storage until capacity of the holding storage is reached. Water in the holding storage then flows by gravity into the cleansing reedbed. The capacity of the reedbed is approximately 25 ML, and it has a surface area of 2 ha. Water is pumped from the reedbed outlet to two storage tanks, and from there it is pumped to the ASTR well field. The ASTR system comprises four injection wells surrounding two recovery wells with 50 m inter-well spacing. The well configuration was designed to produce a mean residence time in the aquifer of 6 months. Water is recovered from the ASTR well field back into two storage tanks, from where it enters the distribution pipeline and is pumped to end-users.

The project has demonstrated that recovered water at the ASTR site generally meets the Australian Water Recycling Guidelines without further treatment. However, further research is needed to test the robustness of the concept, to explore options for harvesting and use of storm water and to assess impacts of its use on water distribution systems.

![Figure 11 Schematic representation of the ASTR scheme in Salisbury, Australia (From: Swierc et al., 2005).](image)
4.3 Aquifer Transfer Recovery (ATR)

As introduced in Chapter 2, Aquifer Transfer Recovery (ATR) is a system of separate infiltration and abstraction wells (‘single purpose wells’), with simultaneous infiltration and recovery in which the infiltration and recovery rates may differ (Figure 12). This type of system is preferred when a continuous water supply is needed and aquifer passage contributes to water quality improvement of the infiltrate (Stuyzand et al., 2012).

How does it work?
Water is injected into an aquifer, displacing the naturally present water in the aquifer.

*Figure 12 Schematic representation of an ATR system with two abstraction wells (adapted from: Peters et al., 1998)*

The water flows through the aquifer towards the abstraction well(s) (Figure 12).

Applications
The principal reasons for ATR applications are disinfection and leveling of the water quality of the infiltrated water by aquifer passage, together with the creation of a buffer to overcome short periods of water scarcity. Research at an ATR site in the Netherlands (Showcase 5) has shown that extraction of water can be continued for a period of at least one month when the infiltration, for example in the case of an emergency, is discontinued. A review by Stuyfzand et al. (2012) shows that ATR systems in the Netherlands range from small scale systems with 4 injection wells to large scale systems consisting of 20 injection wells with recovery wells on both sides of the injection wells. The infiltration capacity of two currently active ATR systems in the Netherlands ranges from 4 to 5.5 Mm$^3$ per year (Stuyzand et al., 2012).

Design issues
The success of an installed ATR system is mainly dependent on the aquifer characteristics and the quality of the infiltration water. To eliminate pathogenic microorganisms a certain transport distance and residence time in the aquifer is required. In sandy aquifers a travel time of 60 to 100 days is generally considered sufficient to remove viruses and bacteria by aquifer passage and to safeguard microbiological safety of the water (Van der Wielen et al., 2008). Hydrological calculations should be made to provide insight in the travel times of infiltrating water.
Showcase 5

Deep infiltration Watervlak (DWAT), the Netherlands

The Provincial Water Authority of North Holland (PWN) started with the ATR project DWAT in 1990. In a review by Stuyfzand et al. (2012) a short description of this system is given.

The objectives of the DWAT system (Figure 12) were storage of water, disinfection, attenuation of the water quality fluctuations in the infiltration water and to meet the drinking water demand. The DWAT system is still operational, although with reduced efficiency. The well field in the coastal dune area consists of 20 infiltration wells with screens at 60-90 m below land surface. The system has a total infiltration capacity of 5.5 Mm$^3$ per year (600 m$^3$ per hour). The maximum realized infiltration is, however, 4.9 Mm$^3$ per year. Recovery takes place using 12 pumping wells with screen at 55-80 m below land surface. The total withdrawal capacity of the system is 540 m$^3$ per hour. During normal conditions the DWAT system is in constant operation with a production of approximately 510 m$^3$ per hour. On an annual basis this amounts to 4.5 Mm$^3$. Less water is abstracted than infiltrated (10% less) to prevent the upconing of saline or brackish water and to allow for extraction in periods when infiltration is discontinued (for example, in the case of an emergency). Research has shown that when infiltration stops, water extraction can be continued for a period of at least one month without extracting saline groundwater (Rolf et al., 2010 and Stuyfzand et al., 2012). Clogging is prevented by reversing infiltration and recovery on a daily basis for about twenty minutes.

Figure 13 Left: Planar view of ATR well field Watervlak (DWAT). The 20 red triangles are infiltration wells, blue dots are the 12 extraction wells.
Operational issues
In the Netherlands several deep infiltration ATR pilots have been conducted since the 1930’s. These initial pilots were without success due to severe clogging of the wells. Only after numerous studies in the 70’s and 80’s did drinking water companies dare to integrate ATR production with existing techniques. An important ATR site is the one called “Watervlak” which was installed by the Provincial Water Authority of North Holland (PWN, Showcase 5). The key factor for this decision was the success in preventing well clogging by advanced pre-treatment of the infiltration water in combination with high-frequent backpumping. The pretreatment consisted of subsequently settling, aeration, coagulation, rapid sand filtration and activated carbon filtration.
5 Conclusions

Research pilots and operational experiences have shown that ASR is a feasible and cost effective method for freshwater supply. There are a large number and growing variety of techniques that can be used for ASR. The development of these new techniques has led to improved ASR performance and demonstrate that recharge, storage and recovery by wells is feasible in aquifers that were previously deemed unsuitable such as thin aquifers, brackish or saline aquifers, and unconfined aquifers. Thus, it is proved that ASR is feasible in a large variety of different settings.

Careful planning is essential to develop a successful ASR system. Recharge objectives, water demand and source water characteristics guide the design and type of ASR system to be constructed. Hydrogeological characterization and operational parameters are essential to determine the feasibility of the project and the design criteria. Also environmental effects and financial feasibility must be considered.

Future research and pilot projects are expected to increase and optimize the application of ASR. New developments will likely further extend the types of aquifers and water types that can be used. Dissemination of knowledge of existing and upcoming projects is essential as it will facilitate project development and risk assessment for new projects. Within the EU FP7 project DEMEAU, the integration of information on many different examples of operational aspects of managed aquifer recharge systems, including ASR plants, is currently prepared for dissemination.
6 Literature


Appendices
I ASR in coastal aquifers for irrigation water supply (poster)

Optimizing small- to medium-scale aquifer storage and recovery (ASR) in coastal aquifers for irrigation water supply

K.G. Zuurhuis 1, 2, P.J. Stuyftand 1, M. Raatman 1, W.J. Zaadnoordijk 1

INTRODUCTION

Aquifer Storage and Recovery (ASR) is defined as the storage of water in an aquifer through a well when water is available, and the recovery by the same well during water demand. Small- to medium-scale ASR systems can maintain a robust and sustainable fresh irrigation water supply in a large Dutch coastal greenhouse area (Figure 1). For this type of ASR in coastal brackish aquifers, estimation of the maximal freshwater recovery is essential. However, in areas less opportune for ASR, optimized injection and recovery using Multiple Partially Penetrating Wells (MPPW) can achieve satisfying ASR performance.

Regional ASR suitability mapping

The performance of ASR in the study area was mapped using high-resolution geological and hydrochemical data, an ASR screening tool (Bolker, 2012) and a Geographical Information System (GIS). This way, we identified promising and unfavorable ASR sites (Figure 2). Clearly, successful small-scale ASR application is extremely site-specific in the coastal area.

Optimizing the ASR Well Design

In an opportune area, an optimized well configuration using Multiple Partially Penetrating Wells in a single borehole (MPPW) was tested in a field trial (Figure 3 and 4). Using this MPPW, the depth interval at which water was injected and recovered could be controlled. By injecting freshwater at the base of the aquifer (winter 2011/2012) and recovering it at the aquifer top (spring, summer), the potential freshwater recovery was tripled, compared to a conventional fully penetrating ASR well.

CONCLUSIONS

Site-selection and local optimization using Multiple Partially Penetrating Wells significantly increase the success of ASR, making it an efficient technology to improve local fresh irrigation water availability. Continuation of the current ASR field trial should further explore the maximum increase in freshwater recovery. Furthermore, water quality changes related to the injection and storage of fresh,oxic rainwater in a brackish, anoxic aquifer are studied, since water quality constraints for the recovered irrigation water are strict.
II Fresh maker and fresh keeper (poster)

Sustainable use and protection of water resources in delta areas: the fresh maker and fresh keeper

Klaasjan Raat¹, Gertjan Zwoikman², Jan Willem Koelmaan³

INTRODUCTION
In coastal areas, fresh groundwater resources are limited and when exploited they are often subject to intrusion of brackish and saline groundwaters. KWR Watercycle Research Institute presents two remedies against these problems: the fresh maker and the fresh keeper. These concepts make it possible to preserve and enlarge fresh groundwater storage and use. Interception of brackish water is the key word in both concepts and, when treated with reverse osmosis (RO), this water forms an additional fresh water source.

THE FRESH KEEPER
In deltas, many abstraction wells suffer from salinization by upconing of brackish water (Figure 2A). The fresh keeper concept provides the remedy. By simultaneously abstracting upper fresh and lower brackish groundwater, the fresh-brackish water interface is stabilized and salinization of the fresh water well is prevented (Figure 2B).

This concept is successfully applied at well field Noordhuizen, the Netherlands (Vivlar Water Company). The abstracted brackish water is used as an additional water source, and so the once abandoned well now produces more water than the original quota.

BWRO: CONCENTRATE DISPOSAL BY DEEP WELL INJECTION
Brackish water is an excellent feed water for RO installations, but large scale application of brackish water RO (BWRO) is hindered by the disposal of the membrane concentrate. At inland sites, deep well injection of the concentrate into a confined, dense saline aquifer is the solution (Figure 2C).

Deep well injection was successfully applied in two field pilots, being technically feasible and environmentally sustainable. A careful selection of source and disposal aquifer is crucial for the success of BWROs and will help to prevent operational problems like membrane scaling and injection well clogging.

THE FRESH MAKER
The fresh maker concept protects natural fresh groundwater lenses by interception of underlying brackish water using horizontal abstraction wells or drains, combination with artificial recharge will even increase the fresh water storage (Figure 2E). This extra water is available for crop irrigation in the growing season (Figure 2F). The use of horizontal wells or drains makes the technique applicable in thin aquifers, which is a prerequisite in many of the world’s delta areas. A field-scale pilot of the fresh maker is foreseen in autumn 2013.

Figure 1: The fresh maker concept. Intelligent abstraction of brackish water increases the storage capacity for fresh water, providing options to preserve and use the fresh water in delta areas.

Figure 2: The fresh keeper concept, in combination with BWRO and membrane disposal through deep well injection.

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