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Enabling the reuse of industrial wastewater to meet freshwater demands of greenhouse agriculture by using aquifer storage and recovery (ASR)

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Abstract: Continuous availability of reliable and high-quality freshwater is a prerequisite for the greenhouse sector. This was not self-evident for Nieuw-Prinsenland, a modern greenhouse area of 260 ha developed in Dinteloord, the Netherlands. Local groundwater is brackish and inflow of fresh surface water is limited. Thus, the irrigation water demand is largely satisfied through collection of rainwater and storage in aboveground basins. However, serious water shortages arise during droughts. A neighboring sugar company produces large volumes of wastewater between September and January, which could form the required additional water source after treatment. Unfortunately, its availability is out-of-phase with the projected demand of the greenhouse sector (April-August). To bridge the gap between availability and demand, a large scale aquifer storage and recovery (ASR) system was realized. A careful path was followed to the realization of the water system, in which the ASR-facility is equipped with an automated control unit and connected to greenhouses, sugar factory, and neighboring food processing industries by a 5 km distribution loop. The system has the potential to supply an additional 300,000 m³ of irrigation water every year, at an average price of 0.51 €/m³. It exemplifies the feasibility of hybrid grey and green infrastructure, and demonstrates how managed aquifer recharge (MAR) can contribute to water reuse in the circular economy. The keys to success are thorough organization, gradual realization, automation, frequent evaluation, and transparent communication.

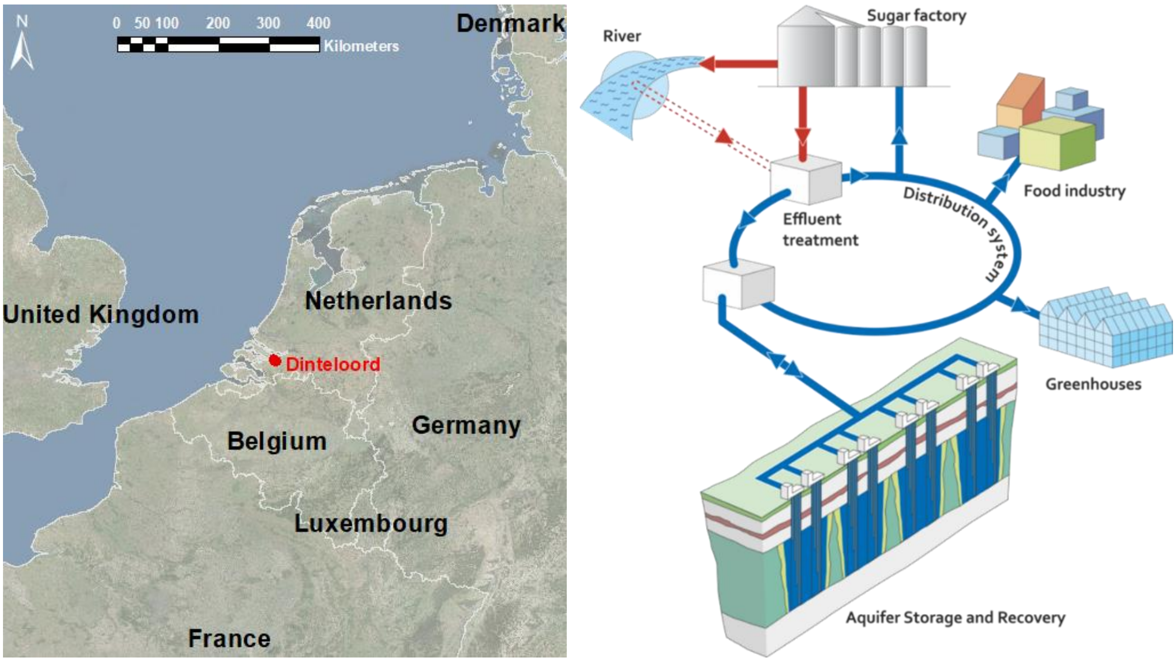
Keywords: MAR; ASR; wastewater; reuse; greenhouse; industry.

1. Introduction

Continuous availability of reliable freshwater is a precondition to meet domestic, industrial, and agricultural demands. Meeting these demands is challenging, especially in areas with a high economic importance, strict water quality requirements, and a limited availability of freshwater. In Dinteloord (Figure 1a), The Netherlands, the Tuinbouwontwikkelingsmaatschappij (TOM) realised the modern greenhouse area Nieuw-Prinsenland (260 ha). The region has a high economic importance for the Dutch greenhouse sector, but is located in a salinizing coastal area without a significant external freshwater supply. Consequently, availability of very high-quality (sodium <2.4 mg/l) water, which is required for greenhouse irrigation, is a major challenge. Rainwater collected at greenhouse roofs and stored in aboveground basins formed the basis for the irrigation water supply. However, these basins can not store sufficient water to overcome years with prolonged periods of drought. Use of groundwater and surface water was prohibited because these sources are threatened by salinization.

Wastewater reuse is recognized as a key solution to deal with water scarcity [1]. In Dinteloord, a sugar factory produces large volumes of wastewater between September and January, and provides a potential irrigation water source for the greenhouse sector. The wastewater can be treated and purified to high-quality irrigation water by using rapid sand filtration, ultra-filtration, and reverse osmosis. Besides treating the reuse water to the desired quality, management of its availability to meet its demand over time is vital for success. In Dinteloord, the availability of wastewater is out-of-phase with the projected irrigation water demand (April-August). The main question therefore was: 'How to transfer the available reuse water to the dynamic time of demand?'

Aquifer storage and recovery (ASR) can provide the crucial solution to the temporal mismatch between availability and demand, and can further safeguard water quality via aquifer passage [2]. In Dinteloord, a wastewater treatment facility is developed and connected to an ASR-system through a 5 km long distribution loop (Figure 1b). The ASR-facility is equipped with eight wells that store and recover treated wastewater between autumn and spring. Multiple partially penetrating wells (MPPW) were installed to counteract buoyancy induced recovery losses [3,4]. The ASR-system has been in full operation since 2018, and has the potential to provide the local greenhouse sector with 300,000 m^3 of irrigation water every year, with a maximum supply capacity of 200 m^3/ h [4,5].



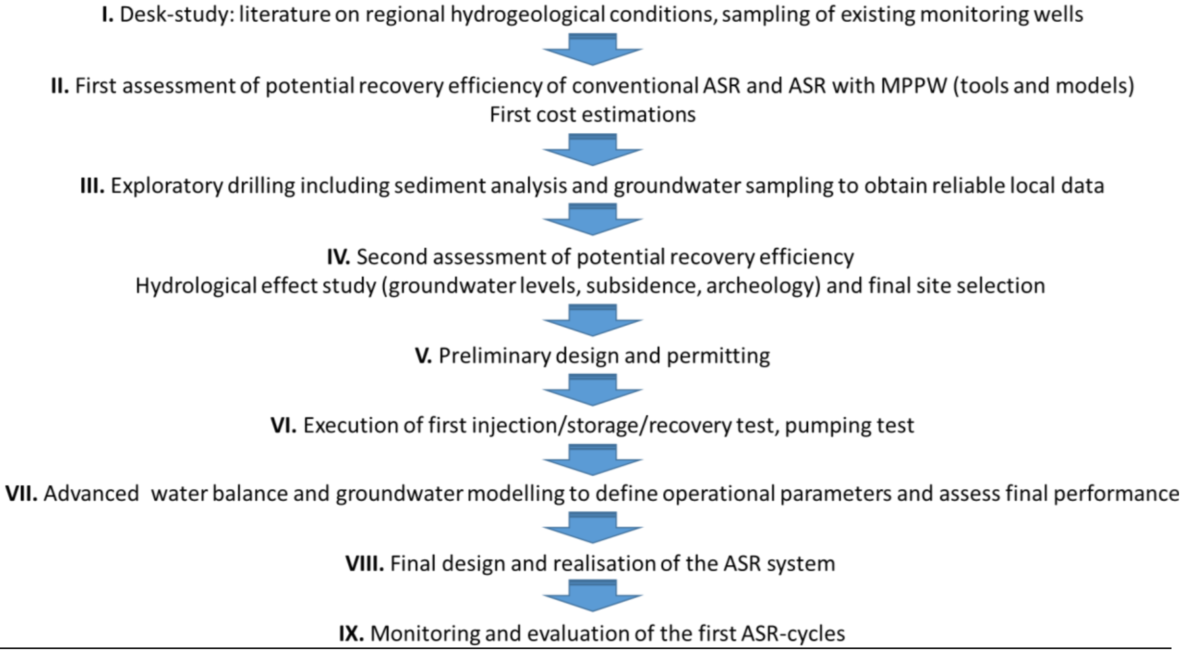
(**a**) (**b**)

Figure 1. (a) Location of Dinteloord; (b) Final design of the Dinteloord water system.

The objective of this paper is to demonstrate the potential of hybrid grey and green infrastructure and to facilitate the development of wastewater reuse systems in combination with MAR in general and with ASR in specific. Therefore, the technical overview and the development of the complete system is explained, the organisational structure is described, the economic feasibility is elaborated upon, and the performance of the system in the first operational years is discussed.

2. Materials and Methods

The Dinteloord water system followed a careful path towards realisation [5]. The complete stepwise approach is listed in Figure 2 and is described in a guiding document [5]. It can be regarded as a guideline for evaluation and implementation of ASR in the scope of wastewater reuse. The most important results of this step-wise approach are further elaborated upon in the next chapter.



I. Desk-study: literature on regional hydrogeological conditions, sampling of existing monitoring wells

II. First assessment of potential recovery efficiency of conventional ASR and ASR with MPPW (tools and models)
First cost estimations

III. Exploratory drilling including sediment analysis and groundwater sampling to obtain reliable local data

IV. Second assessment of potential recovery efficiency
Hydrological effect study (groundwater levels, subsidence, archeology) and final site selection

V. Preliminary design and permitting

VI. Execution of first injection/storage/recovery test, pumping test

VII. Advanced water balance and groundwater modelling to define operational parameters and assess final performance

VIII. Final design and realisation of the ASR system

IX. Monitoring and evaluation of the first ASR-cycles

Figure 2. Stepwise approach followed to enable water reuse in Dinteloord [5].

3. Results

3.1. Hydrogeology

3.1.1. Characterization of the target aquifer

The subsurface is characterized in existing literature [5]. Its main characteristics are briefly presented in Table 1. The target aquifer is about 18 meters thick and consists of (medium) fine sand with a thin clay layer at medium depth. The target aquifer is confined by fine heterogeneous sediments with a total thickness of about 10 meters. A sandy clay forms the base of the target aquifer.

Table 1. Characterization of the target aquifer (m ASL is the abbreviation for meters above sea level).

Layer top [m ASL]	Layer bottom [m ASL]	Formation	Lithology	Layer type
0	-10	Naaldwijk	Clay, fine sand, peat	Aquitard
-10	-20	Waalre	Fine sand, clay layer at the base	Target aquifer
-20	-28	Waalre	Medium fine sand	Target aquifer
-28	-32	Waalre	Sandy clay	Aquitard

3.1.1. Characterization of the native groundwater

The transition from saline to fresh groundwater is situated within the project area [5] (Figure 3). The regional occurrence of saline groundwater results from flooding and consequent infiltration of seawater in the Holocene, until closure of the North Sea estuaries in the 1970's. Three monitoring wells were used to determine the actual distribution of fresh and saline groundwater. Chloride concentrations observed in the target aquifer in the north of the project area range from 1000 mg/L to 4500 mg/L, which is too high for an efficient implementation of ASR. Deeper aquifers are more saline and thus even less suitable. In contrast, chloride concentrations observed in the target aquifer in the south of the project area are remarkably lower and vary between 25 mg/L and 60 mg/L. Moreover, groundwater flow is virtually absent, making the southern part of the project area the most suitable location for realisation of the ASR-system (Figure 3).

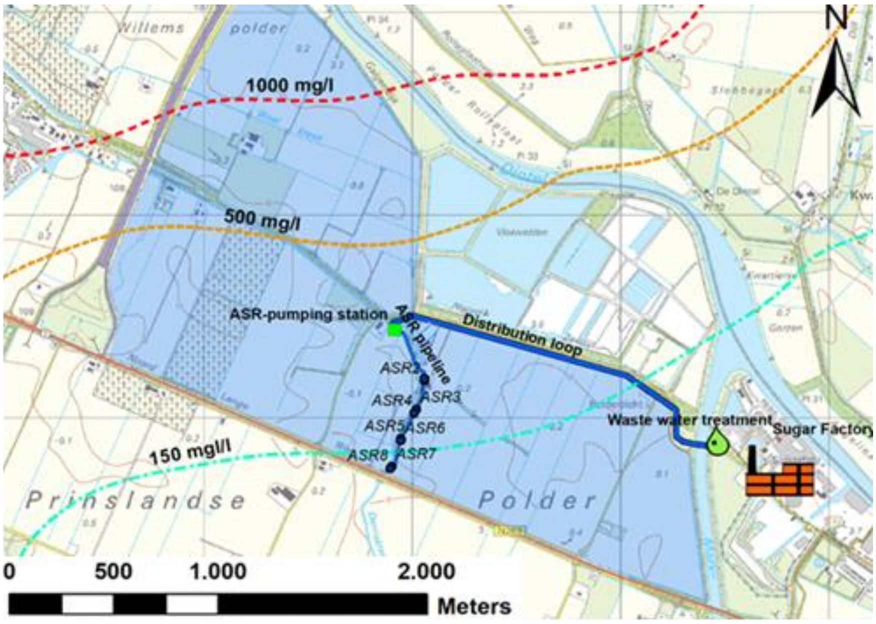


Figure 3. Overview of the project area. The red, orange, and blue contours represent estimated chloride concentrations of native groundwater [5].

3.2. ASR system

The first pilot ASR-well consists of four partially penetrating wells that can infiltrate or recover water independently (Figure 4). Recovering only with shallow partially penetrating wells allows counteracting buoyancy induced recovery losses resulting from the density difference between stored fresh water and brackish ambient groundwater [3]. Since buoyancy effects were not as significant as expected, the seven additional ASR-wells were later installed with only two well screens.

The ASR-system is equipped with an automated control unit to regulate infiltration and recovery automatically based on the irrigation water demand of the greenhouse owners and the availability of treated effluent [5]. It ensures a minimum infiltration rate of 60 m^3/h and a maximum recovery rate of 200 m^3/h. The unit records operational data and sends alarms upon disruptions. It can be operated on site with a touch-screen or remotely with a computer program, and thus allows for the manual regulation of rates, volumes, and settings whenever desired or required [5].

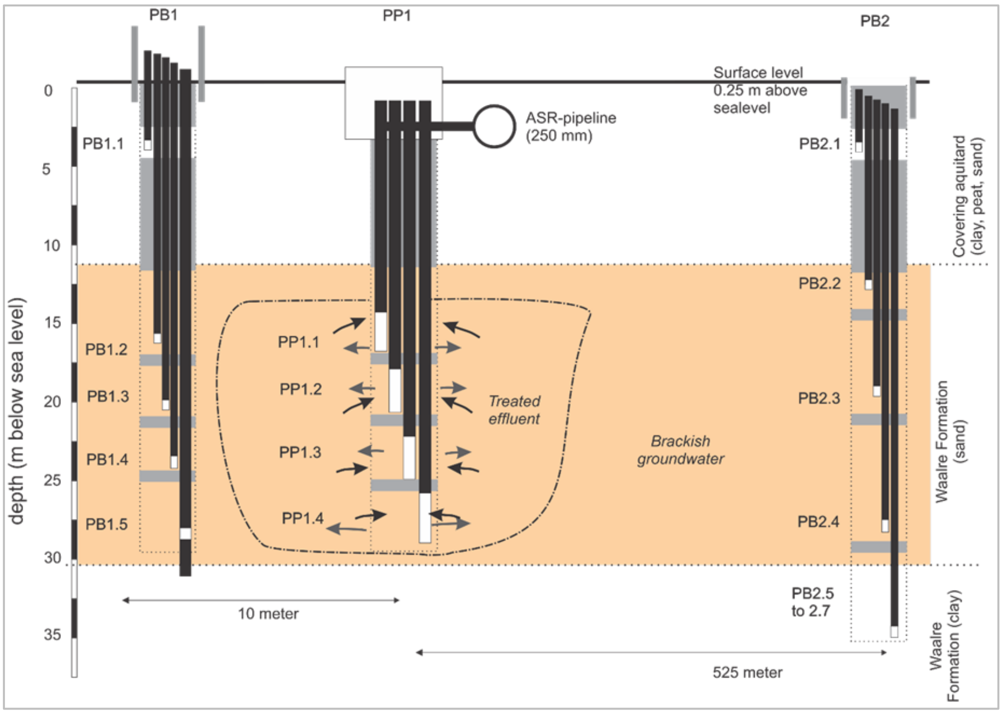


Figure 4. Well configuration of the pilot ASR-well (PP1) and two monitoring wells (PB1 and PB2) [5].

3.3. Water balance

3.3.1. Water balance model fundamentals

The water balance of the Dinteloord water system is composed of two main storage reservoirs:

1. The surface storage basins of greenhouse owners (*B*);
2. The subsurface as the storage reservoir for ASR (V_{ASR}), with a maximum capacity of 300,000 m^3.

The fluxes affecting both reservoirs are given in Figure 5 [5]. *B* is linked to V_{ASR} through the infiltration (ASR_{rw}) and recovery (ASR_{sup}) fluxes of the ASR-facility, having rates of 1,440 m^3/day and 4,800 m^3/day, respectively. Furthermore, *B* is fed by net precipitation intercepted by greenhouse roofs (I_{Roof}) and aboveground basins (I_{Basin}). Water stored in *B* is utilized by greenhouse owners for their water demand (*D*) and can leave the system by basin overflow (*BO*). The sugar factory refines sugar from April 1 to June 15, requiring 25,000 m^3 of water and producing 500,000 m^3 of wastewater. The sugar beet campaign runs from August 15 to September 1, requiring 5,000 m^3 of water and producing at least 1,500,000 m^3 of wastewater. The wastewater is treated and supplied at a maximum rate of 1,440 m^3/day (*IWD*). The treatment plant can operate on river water during calamities or when wastewater is unavailable. *SFU* represents water (re)used by the sugar factory.

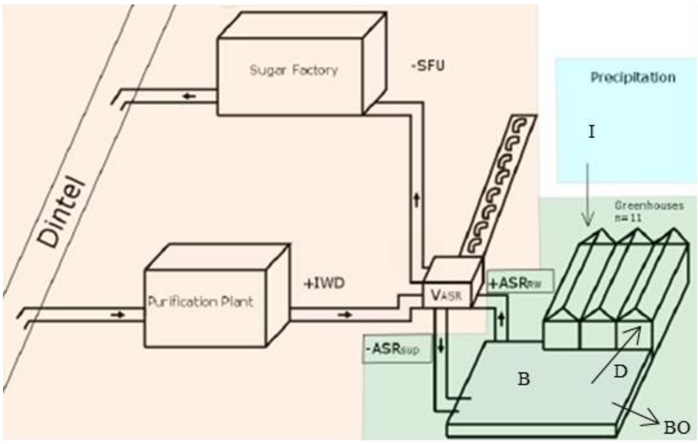


Figure 5. Schematic representation of the total water balance of Dinteloord [5].

3.3.3. Modelled results 2000-2016

The water balance was modelled with local weather data for 2000-2016 (Figure 6). The inclusion of ASR and water reuse keeps water shortages below 20,000 m^3/year, with an average shortage of about 5,000 m^3/year. This shortage is only 2.5% of the annual average volume supplied by ASR (203,056 m^3), i.e. the shortage that would occur without ASR. Water shortages mainly occur during extended periods of drought, and are limited by the infiltration and recovery rates rather than the stored capacity. The stored volume only becomes limiting at low capacity, as mixing with ambient brackish groundwater is more significant. The model reflects a resilient cooperation between individual greenhouse owners and the ASR buffer, even during a prolonged drought in 2013. The only risk lies in consecutive dry years, possibly resulting in insufficient ASR replenishment and a consequential unavailability upon demand. Thus, annual supplementation of treated effluent to the subsurface is important, and supply of stored water to the greenhouse owners should occur betimes.

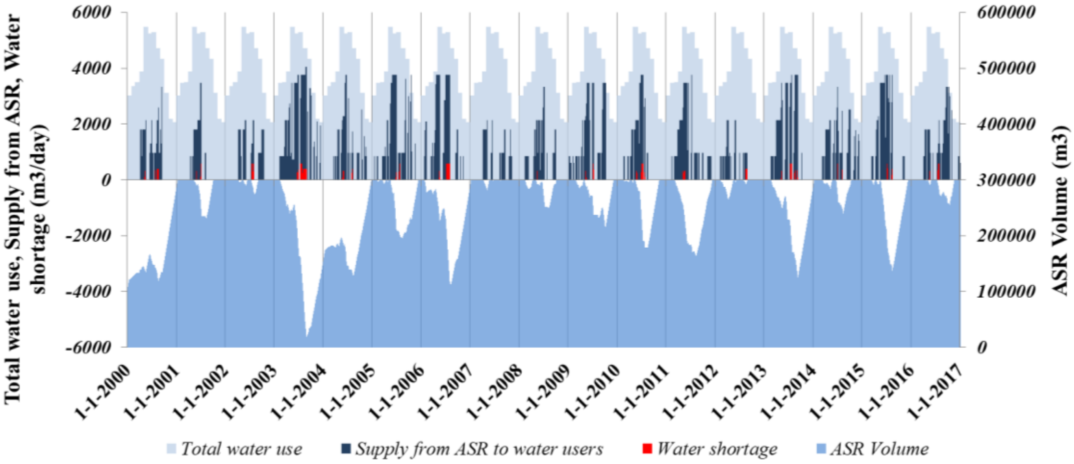


Figure 6. Water balance results modelled with weather data of 2000-2016. Water shortage is the water demand that can not be satisfied by precipitation stored in surface basins, by direct supply of treated effluent, or by water recovered from the subsurface via ASR.

3.4. Monitoring and evaluation of the ASR performance

3.4.1. Water quantity

The first ASR-well was realized in February 2016 for a pilot on a small controllable scale (Figure 7). During this ASR-pilot, 12,748 m^3 of treated wastewater was infiltrated. After six months of storage, 1,470 m^3 was successfully recovered and met the strict water quality requirements for irrigation. Three additional ASR-wells are operating since June 1st of 2017. The last four wells were realized in 2018 and the ASR-system has been in full operation since March 6th of that year. In total, 271,889 m^3 has been infiltrated and 108,164 m^3 has been recovered and supplied upon demand. This amounts to a net infiltration of 163,726 m^3 and a recovery efficiency (RE) of 40% (Figure 7). This low RE is not entirely due to water quality restrictions or an insufficient recovery rate. The results do not include the recovery phase of 2019. In addition, when an ASR-well is taken in operation, a freshwater lens first has to develop in the subsurface for later use [6], i.e. the potential RE increases when net infiltration reaches the target storage volume of 300,000 m^3, as water quality limitations are less significant (see 3.3.3.). The actual RE can only be determined for full hydrological years after attaining the target storage volume. The most valuable results so far are obtained from ASR1 for the hydrological year 2016-2017. ASR1 recovered 80% of the infiltrated water with a suitable irrigation water quality (sodium <2.4 mg/L). Moreover, the ASR-facility supplied the already established greenhouse owners with sufficient reuse water during the dry summer of 2018, whereas greenhouse owners with conventional water supply systems already ran out of their supplies a month earlier.

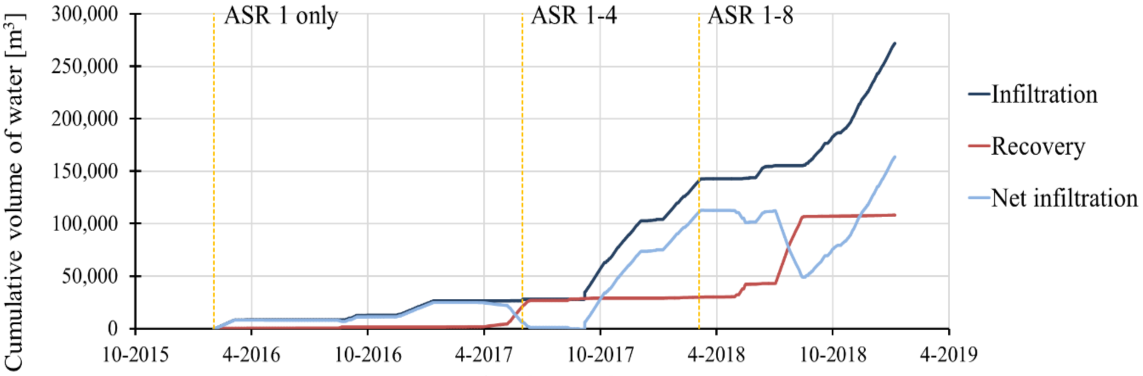


Figure 7. Performance of the ASR-system in the period 2016 – 2019.

3.4.2. Water quality

Sodium appeared to be the solute limiting the recovered water quality, with a maximum allowable concentration of 2.4 mg/L for irrigation. Moreover, exploratory drillings have revealed the presence of pyrite (FeS_2) and siderite ($FeCO_3$) in the subsurface. Oxidation of these minerals by continuous intrusion of oxygen via inadequate vent valves during infiltration and storage resulted in mobilization of iron. However, after aerating the recovered water in surface basins, mobilized iron settled out as iron oxides and operational problems were not observed. In addition, mobilised iron appeared to decrease over successive ASR-cycles, reducing the risks for irrigation. Mobilization of arsenic by oxidation of pyrite was neither observed to be a threat for the recovered water quality. The exploratory drillings have revealed a relatively high content of carbonates in the subsurface. Dissolution of these carbonates buffers the acid produced by oxidation of pyrite and siderite, thereby increasing the hardness of recovered water during recovery. This did not result in operational problems in Dinteloord, but might do so elsewhere.

3.5. Organizational structure

Using wastewater from one party for later use (after aquifer storage) by a second party involves clear agreements between the different parties involved. In Dinteloord, all parties were organised to properly operate and administrate the entire water system, and responsibilities have been distributed (Figure 8). The greenhouse cooperation, including its eight members, has a central role as owner and main end user of the water system. Veolia is operating the wastewater treatment system, while TOM and KWR operate the ASR-system. TOM is the developer of the greenhouse area, and Codema is the engineering company that constructed the ASR-system and is responsible for its maintenance. KWR was involved with the design and development of the ASR-system. KWR is also responsible for monitoring and evaluation of the ASR-system's performance, and is consulting partner for the TOM and the Water authority Brabantse Delta, manager of the local surface water system. Suiker Unie provides wastewater but is also end user of the treated water. The Province of Brabant was the permitting agent for the ASR system.

The maximum volume of fresh water that can be recovered by ASR and supplied to the users may vary every year. Each spring, KWR estimates the recoverable freshwater volume, upon which TOM distributes the water over the users. The recovery rate is limited to 200 m^3/h, i.e. 1 m^3/h per hectare of greenhouse area. The minimum guaranteed supply rate for each user is based on this rate and their greenhouse area. Users with a lower water demand can transfer their rights to users with a higher demand. These transfers must be communicated to TOM, which executes the billing. The costs are covered by a pay-per-use system through the price of a cubic meter of water (Figure 8).

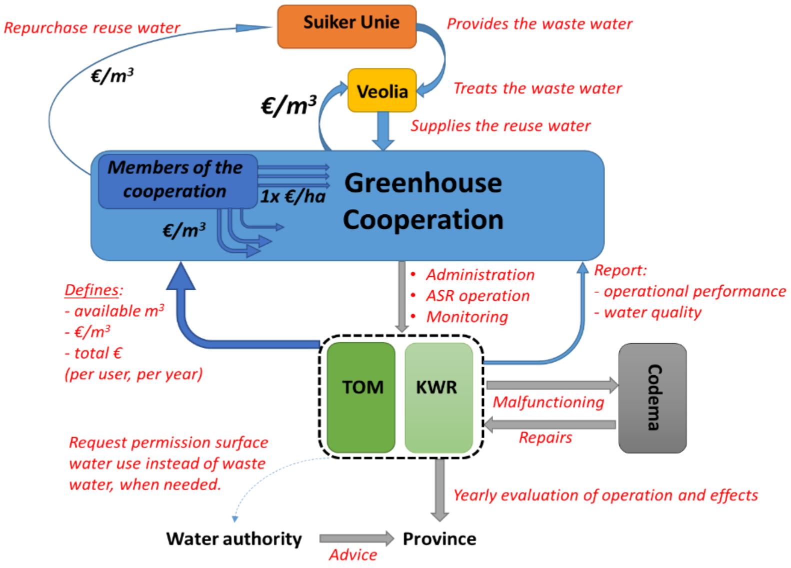


Figure 8. Organogram of the Dinteloord wastewater reuse system including ASR.

3.6. Economic analysis

The costs of the Dinteloord water system are twofold:

1. Investment costs or capital expenses (CAPEX): the total costs made to realize the installations, e.g. the wastewater treatment system, pipelines, pumping stations, and ASR-wells;
2. Variable costs or operational expenses (OPEX): costs made to operate the system. This includes costs for treatment, electricity, and monitoring. It also entails the costs for advice, maintenance, and evaluations. OPEX are calculated at the end of a year and may vary over the years, depending on the need for maintenance and the volume of water treated, stored, and supplied.

An economical model was made on the basis of CAPEX, OPEX, and relevant economical parameters, like financial depreciation and fiscal impact [7]. The main economical parameters are listed in Table 2. Based on these parameters, the price of a cubic meter of water supplied amounts to 0.51 €/m^3 [7]. This is competitive with local tap water, having a price of 0.43 €/m^3 for a normal connection and 0.90 €/m^3 for a temporary connection. However, local tap water requires additional treatment and thus costs, since its high sodium content does not allow for direct irrigation.

Subsurface water storage by ASR is especially cost-efficient compared to the alternative of aboveground storage, which has an estimated price of 1.06 – 3.09 €/m^3, depending on the basin's location and lifetime. These costs are dominated by the production loss related to aboveground space requirements and by more significant reinvestment costs due to a shorter life-time (15 years). CAPEX of ASR is lower compared to aboveground storage, whereas OPEX are slightly higher, due to the electricity needs for wastewater treatment and pumping to and from the subsurface [7].

Table 2. Economical input parameters [7].

Parameters	Value	Unit
Lifetime of the ASR-system	20	years
Initial investment costs	892 000	€
Reinvestment costs	112 900	€
Operational/variable costs	21 250	€/year
Average annual water injection	125 000	m^3/year
Average annual water recovery	125 000	m^3/year
Maximal annual water recovery	300 000	m^3/year
Required maximal volume to supply	300 000	m^3
Active surface area of water system	200	ha

4. Discussion and conclusions

The system in Dinteloord reveals that implementing ASR with treated wastewater is a viable and economic feasible strategy to automatically supply high-quality irrigation water to local greenhouse owners upon demand. Space requirements are negligible compared to aboveground storage, the subsurface acts as an additional treatment step for stored water, water shortages can be reduced by 97,5%, and average costs of supplied water are competitive with local tap water. Water supply by the ASR-facility in Dinteloord is limited by the infiltration and recovery rates rather than the stored capacity. Thus, annual supplementation of treated wastewater to the subsurface is important, and delivery of water stored in the subsurface should occur betimes. A resilient cooperation between individual greenhouse owners and the ASR buffer can exist, even during a prolonged drought. The only risk appears to lie in consecutive dry years. The most important lessons learned from implementing ASR for water reuse are [5]:

- Take it step-by-step: Various elements can fail when applying ASR with treated wastewater. A careful step-by-step approach with a critical but open perspective is required for realization. Perform a desk study, verify important assumptions with field measurements and models, and validate and demonstrate with a small-scale pilot. Technical feasibility, economic viability, and hydrological acceptability should constantly be assessed in an iterative process. Targeted end users, authorities, neighbors, and the wastewater supplier should be continuously informed.
- Demonstrate and communicate: Water reuse and ASR both involve complex technologies and processes. A clear demonstration and communication towards stakeholders, end users, and the public is vital. For Dinteloord, this was achieved by information panels, an informative movie, a public opening, and an article in a professional journal with details on the complete set-up [8]. End users were particularly informed by regular meetings with the cooperation. Participatory technology assessment sessions were organized to inform a broad range of stakeholders [9].
- Set up the organizational structure: Implementing water reuse and ASR with multiple end users requires a firm organizational structure with clear roles for every party. In

Dinteloord, the organization was set up by TOM, a stable, central party with a good overview of all processes. TOM was able to assess the technical and economic viability based on data provided by experts.

During the development and in the coming years, the water system in Dinteloord is intensively being controlled, monitored, and evaluated. This involves mainly to appropriately distribute infiltration and recovery over the various well screens, to examine water quality changes occurring during storage (KWR), to repair potential malfunctioning of the system (Codema), to record and report quantitative data, and to coordinate all aspects of the cooperation (TOM).

In short, the story of Dinteloord perfectly exemplifies how MAR and collaboration between multiple parties can bridge the seasonal gap between the availability of wastewater and the demand of irrigation water, and can contribute to the business case of water reuse in a circular economy.

Supplementary Materials: The following is available online at https://vimeo.com/256952109, Video S1: Water reuse and aquifer storage and recovery Dinteloord.

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Author Contributions: T.C.G.W. van Dooren monitors and evaluates the ASR performance in terms of water quantity and quality, analyzed the data of the first operational years, and wrote this paper. K.G. Zuurbier was involved in the geohydrological research and the technical design, and monitored and evaluated the ASR system throughout the years. N. Hartog assisted in interpreting the geochemical results and their influence on the ASR performance. K.J. Raat is the project manager and P.J. Stuyfzand is the quality assurer of the project.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations:

The following abbreviations are used in this manuscript:
ASR: Aquifer storage and recovery
MAR: Managed aquifer recharge
TOM: 'Tuinbouwontwikkelingsmaatschappij' (Dutch)
MPPW: Multiple partially penetrating wells
RE: Recovery efficiency
CAPEX: Capital expenses
OPEX: Operational expenses

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