Netherlands Journal of Geosciences

Original Article

Cite this article: Guilherme E.H. Nogueira et al. Flexible solution concepts for sustainable drinking water production in the Netherlands. *Netherlands Journal of Geosciences*, Volume 104, e11908. https://doi.org/10.70712/NJG.v104.11908

Received: 05 February 2025
Revised: 08 February 2025
Accepted: 20 January 2025
Published: 19 February 2025

Keywords:
Sustainable water supply; flexible groundwater extraction; global change; the Netherlands; managed aquifer recharge (MAR)

Corresponding author:
Guilherme E.H. Nogueira
Email: guilherme.nogueira@deltares.nl

Supplementary material:
The supplementary material for this article can be found at https://doi.org/10.70712/NJG.v104.11908.

Flexible solution concepts for sustainable drinking water production in the Netherlands

Guilherme E.H. Nogueira[1], Rianne Meeusen[1], Renske C. Terwisscha van Scheltinga[2], Tom Hoogland[2], Stefan Jansen[1], Geert-Jan Nijsten[1], Janneke Pouwels[1], Peter H. Kuin[4], Jos H. Peters[4], Hilde F. Passier[1] and Perry G.B. de Louw[1,3]

[1]Deltares, Utrecht, The Netherlands; [2]Vitens NV, Zwolle, The Netherlands; [3]Soil Geography and Landscape, Wageningen University & Research, Wageningen, The Netherlands; [4]Royal HaskoningDHV, Amersfoort, The Netherlands

Abstract

The challenges of providing sustainable drinking water are growing due to resource mismanagement, contamination threats and rising demand, which are further intensified by climate change. This further underscores the need for building-in resilience in existing extraction points to gain flexibility against uncertain and unforeseen developments. Although invisible, groundwater is a key drinking water source globally, including in the Netherlands, where over 60% of drinking water comes from it. The Dutch regulations, limited space and competition for water require adaptive strategies that enhance sustainability in water provision. Here, we identified and categorised various groundwater and surface water extraction archetypes in the Netherlands based on land use, extraction depth and local geology, assessing their susceptibility to contamination and operational challenges. Then, we evaluated four solution concepts to enhance sustainability in drinking water supply: the *Water Battery* (large-scale managed aquifer recharge), *Fresh/Salt extraction* (mitigated coastal salinisation), *Switching between extractions* (balancing demands in space) and *Resource City* (promoting circularity in urban water supply). Practical examples are already in place in the Netherlands as the Epe Water Battery shows successful infiltration and storage of groundwater to meet local demands and avoid undesirable low groundwater levels. We also explore the legal and operational challenges, emphasising stakeholder collaboration, proactive policies and the need for strategic investments in water quality improvement for a resilient, sustainable water supply in the face of climate change.

Introduction

According to the United Nations and the World Bank, around 2 billion people lack access to safe drinking water worldwide, and this number will likely increase to nearly 3 billion people in 2025 (UNESCO, 2023). Mismanagement of resources, contamination and the impacts of climate change are intensifying strain on our water resources (Calverley & Walther, 2022; DutchNews, 2023; Gelati et al., 2020; Toreti et al., 2023), which increase pressure for drinking water production. Groundwater (GW) serves as a crucial source for drinking water on a global scale. And this certainly applies for the Netherlands, where more than 60% of drinking water comes from groundwater sources (VEWIN, 2020). Thus, Dutch groundwater extraction permits are subject to stringent regulation, mainly to prevent excessive damage to groundwater-dependent ecosystems. Although the abstractions are in equilibrium with groundwater recharge, and aquifer depletion has not yet been observed in the Dutch context, abstractions may reduce groundwater levels and groundwater discharge to streams, thus stream flows. Also, the limited available space to facilitate all land-users and intensive agriculture enhances competition for water and contamination risks (e.g. high Nitrate and fertilisers loads).

Approximately 25% of the Dutch territory is below sea level, where saline groundwater is found close to surface, and salt loads to the surface water system via saline seepage are high (De Louw, 2013; Delsman, 2015). Anticipated sea level rise increases threats from seawater intrusion, further decreasing freshwater availability and reducing suitable areas for drinking water production (KNMI, 2023; Oude Essink, 2001; Oude Essink et al., 2010; Werner et al., 2013). Scenarios from the Netherlands Environmental Assessment Agency (PBL, 2014) indicate that by 2027, between 60 and 95% of Dutch surface waters will not fulfil the standards established under the Water Framework Directive (WFD, 2000). Pollution of surface water will increase pressure on groundwater for drinking water production. RIWA-Meuse (2023), for example, disclosed 62 stops (a total of 5,585 hours) due to water pollution in 2022. Furthermore, drinking water demand will proportionally increase as the world population increases, a similar scenario for the Netherlands, where projections estimate more than 20 million people by 2070 (CBS, 2020a). These changes not only stress the capacity of traditional water infrastructure but also underscore the need for adaptive strategies to mitigate risks and ensure sustainable water provision (McEvoy et al., 2020; Van de Ven et al., 2016).

Applications of techniques as Managed Aquifer Recharge (MAR) for increasing freshwater availability are growing globally (Fathi et al., 2021; Hiscock et al., 2024; Stefan & Ansems, 2018). However, not every location is suitable, and other management practices are required (McEvoy et al., 2020). Where space is limited, and the water system is already under pressure as in the Netherlands, adaptive concepts to (sustainably) explore water resources for drinking water production are needed to keep up with climate changes, competing claims and population growth. Such strategies require flexibility of water providers to fluctuations in demand and in water resources, whilst ensuring their further sustainability.

One of the difficulties to keep up with sustainability is the inflexibility of existing water supply infrastructures at extraction sites: it is not easy to switch between sources to serve a specific demand under extra, unforeseeable hydroclimatic stresses. This can lead to water gaps (e.g. demand >> supply) and overexploitation of sources. Engineering interventions as supply-storage (Winpenny, 1997) in which water managers should make better use of existing resources rather than installing new supply sources are well known but, in practice, are rarely implemented (Scheierling & Tréguer, 2018). Moreover, developing a new drinking water extraction site can take years in the Netherlands, which requires planning. Finally, land use that relies on groundwater levels (as sensitive crops, natural ecosystems like wetlands) can be significantly impacted by groundwater depletion, requiring sustainable management practices, and can pose challenges when scaling up existing extraction points to accommodate sudden changes in water demand.

To that end, this paper highlights and discusses solution concepts for enhancing flexibility at drinking water extraction points, encompassing design, evaluation and implementation. Whilst specifically tailored to the Dutch context, these approaches are transferable and applicable to other regions as well. First, we provide a short description of the main extraction setups existing in the Netherlands, referred to as extraction archetypes, based on type of water source, local geology, extraction depth and land cover. Then, we provide a list of solution concepts to increase water supply flexibility and show examples where they are being implemented and investigated. Finally, we discuss the pros and cons of the concepts, and some of the legal and operational challenges to their implementation. Combining empirical observations, expert knowledge and model estimates, we aim to show the advantages and importance of the solution concepts for flexibility in water supply.

Extraction archetypes and solution concepts

Classification of archetypal groundwater extraction sites

In total, there are approximately 200 locations in the Netherlands, where groundwater and surface water are extracted for drinking water production (RIVM, 2018). According to a report from VEWIN (2020), 57% of the drinking water comes from groundwater, and approximately 36% comes from surface water (e.g. direct intake from rivers, Ijsselmeer Lake). The remaining 7% is related to riverbank filtration (RBF) sites and the so-called dune-water (i.e. infiltration, purification and extraction of infiltrated water in the dunes). Overall, more than 60% of the drinking water in the Netherlands is extracted as groundwater. Based on different land uses, extraction depths and local geology, we identified nine different extraction archetypes. They characterise the main types of extraction sites and form the basis of GW and SW extraction in the Netherlands (Figure 1). A brief description of each archetype is provided in Figure 1.

A: *Shallow groundwater extraction (agricultural and natural environments):* This archetype is characterised as shallow (unconfined) groundwater extraction in both agricultural and natural environments (typically occurring at depths between 20 and 60 m). It is the most common type of GW extraction in the Netherlands due to the predominance of agricultural land use, with forests and natural areas being the second most common land use (CBS, 2020b). The main risks for this archetype are related to land use, point sources of chemical pollutants and diffuse application of fertilisers and pesticides, and eutrophication of nearby SW bodies that can impact GW quality depending on their connectivity. This archetype is classified as moderately vulnerable due to regulations in groundwater protection zones.

B: *Deep groundwater extraction:* This archetype is defined by deep GW extraction wells (typically deeper than 60 m) in semi-confined and confined aquifers. One of the biggest risks of this archetype is groundwater salinisation (upconing), particularly when extraction takes place close to the fresh-saline water interface. This archetype is classified as least vulnerable due to great distance to the surface and the presence of a (semi-) confining layer above the aquifer unit, both increasing the travel time of infiltrated rainwater to the extraction wells and reducing risks of surface contamination.

C: Shallow groundwater extraction (urban environment): This archetype is characterised as a shallow (unconfined) groundwater extraction in the proximity of urban environment. The greatest risks for this archetype are related to surface activities in urban areas, which can lead to the occurrence of chemical point pollutants, organic micro-pollutants, proximity to (former) landfill sites and the inflow of water from wastewater treatment plants (WWTPs). This archetype is classified as vulnerable.

D: Riverbank filtration (RBF) sites: This extraction type is characterised by extraction wells near riverbanks, allowing river water to pass briefly through the subsurface before extraction. RBF, considered a type of managed aquifer recharge (MAR) technique, is widely used in Europe (Stefan & Ansems, 2018). This archetype is classified as vulnerable. The biggest risks for this archetype are upstream contaminations and WWTP effluent that can impact surface water quality, thus GW due to direct connection between aquifer and stream water.

E: Surface water extraction with basins: This extraction is characterised by surface water intake into large (process) basins (where waters are pre-treated) prior to infiltration. The extraction of Evides in the Biesbosch and PWN in the Ijsselmeer Lake (fed by the river Rhine) serves as examples. This archetype

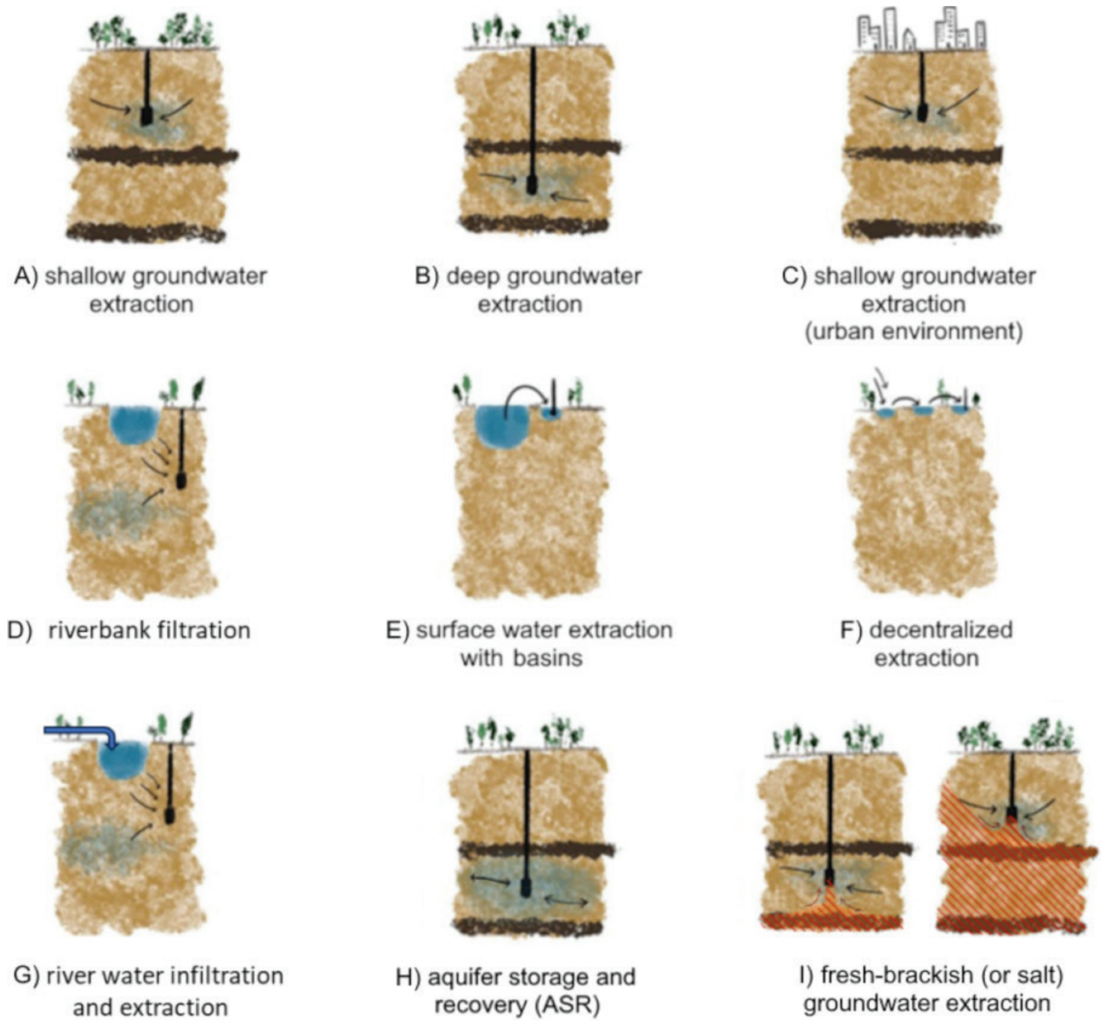


Figure 1. Main archetypal extraction sites.

is classified as vulnerable. Risks for this archetype are like RBF archetypes, and any activity in the catchments can lead to the occurrence of organic micropollutants and contaminants affecting surface water quality.

F: Decentralised extraction (mixed sources): These are typically a combination of surface water, groundwater, water reuse from industry or WWTP and RainWater Harvesting (RWH). This is an unconventional extraction, and the Dutch drinking water law prohibits the use of harvested rainwater for applications other than toilet flushing (Hofman-Caris et al., 2019). Nevertheless, this is different in other countries, and important examples of this archetype worldwide are the '*sponge cities*' in China (Wang et al., 2018) and the RainWater Harvesting initiatives in South Korea (Han & Mun, 2011). Therefore, we included this archetype in our analysis. This archetype is classified as vulnerable. Risks for decentralised extraction include occurrence of organic micropollutants, toxins of microbial origin and mixing with WWTP water.

G: River water (in)filtration and extraction: This archetype involves the uptake, pre-treatment and transport of river water over a distance into basins, allowing infiltration and storage into a shallow (unconfined) aquifer. This archetype is also an example of MAR. Amongst many examples of such archetype in the Netherlands, one is the dunes system near Amsterdam (Geelen et al., 2017). The great risks for this archetype are the occurrence of organic micropollutants and other contaminants on river water, which can increase pre-treatment costs and potentially lead to intake stops.

H: Aquifer storage and recovery (ASR): This archetype intends to inject water into an aquifer during times of surplus for later extraction during periods of scarcity. This archetype is also an example of MAR usually applied to recharge deeper confined aquifers units. The ASR includes deep wells that can serve double purposes of injection and extraction (INOWAS, 2018). High-quality water is required to prevent clogging and pollution of the aquifer unit. This archetype is classified as least vulnerable due to strongly regulated water quality and distance to surface activities.

I: Brackish-saline groundwater extraction: This is an unconventional archetype that refers to exploitation of aquifers containing a mixture of fresh and slightly saline (brackish) water. This is typically found in coastal regions where freshwater from rivers or rainfall interacts with seawater, leading to transition zones where salinity gradually increases. In the coastal area of the Netherlands, brackish to saline groundwater is found at shallow depth ranging from several metres to 50 metres depth. Extracted (brackish) water can be targeted to industrial uses (e.g. cooling water for power generation, mining, oil and gas industries) where water quality standards and salinity levels are less strict. Once desalinated (or mixed and diluted), it can also be used for drinking water and growing crops(FAO & AWC, 2023). One of the side effects is the large amounts of brine resulting from desalinisation.

Solution concepts for flexible extractions

The abovementioned extraction archetypes together provide the needed water under normal circumstances. However, with accelerated urban growth and more extreme climatic events, the supply of clean and sufficient water is under pressure. Recently, water supply companies have focused on making extractions more resilient to demand fluctuations and climate changes through integrated management and long-term plans that address various hydroclimatic stresses, enabling multiple solution concepts.

The solution concepts aim to improve flexibility with respect to the following criteria:

- Increase in flexibility: general ability to cope with fluctuations in demand and water stresses;
- Resilience to climate change: adaptability to changes in rainfall and temperature patterns that can affect water availability;
- Scalability: ability to scale up and scale down production capacity at short notice (e.g. months);
- Source water quality: ability to accommodate changes in water quality;
- Cost-benefit aspects: technical challenges and costs of installing and maintaining systems.

We focus on expected changes in drinking water extraction dynamics and solutions for a time horizon of about 100 years from now. Based on work from Maring et al. (2022), four different solution concepts were outlined to enhance flexibility of extraction archetypes for water supply. These are:

1) *Water Battery*: large-scale MAR to store water in the subsurface for later extraction;
2) *Fresh/Salt, extraction of saline/brackish groundwater*: approaches to deal with extraction at coastal aquifers threatened by seawater intrusion and groundwater salinisation;
3) *Switching between extractions*: techniques to minimise overexploitation of aquifer units by switching between extraction points (over space and/or time);
4) *Resource City*: solutions for self-sufficient cities in terms of water supply. This concept uses several building blocks that together ensure enough clean water available.

We recognise that there might be other variations of solutions for different archetypes. However, with our study, we aim to highlight some of the benefits of those concepts for flexibility in water supply, rather than cover all possible solutions. Figure 2 summarises how the different solution concepts can be linked to different archetypes (where we can apply what), as well as how the concepts compare to each other in the different criteria. One solution concept can be applied to multiple extraction archetypes depending on adaptability and local conditions. The various concepts demonstrate positive scores for flexibility and resilience to climate change. However, they differ in scalability, source-water quality and cost-benefit aspects. We emphasise that scores are more indicative and based on expert knowledge and previous experiences, whereas future studies could focus on refining such marks. The main aspects, limitations and some examples of the solution concepts are presented in chapter 3.

Solution concepts and examples of applications

In this section, we describe the four different solution concepts that can aid in tackling water supply gaps by offering flexibility for the archetypical extractions presented before. Different approaches and management strategies are presented for each solution concept.

Water Battery (infiltration and storage of SW and riparian GW)

The concept of Water Battery refers to actively infiltrate water (artificial recharge) and storing it in the subsurface for future use. It is a form of MAR and not a new concept – but one that still has its potential undervalued in the Netherlands. It is a key element that bridges the gap between (rain or river) water excess in winter periods and higher water demand in summer period. The quality of source water is decisive. Waters from local streams and springs discharging groundwater originated from natural areas are relatively clean and can be safeguarded, thus are most desirable.

Artificial infiltration also has several ecological benefits. The water infiltrating at highest points in the topography (Figure 3) percolates to the deep groundwater system, and the long travel-time from infiltration to extraction results in water quality improvements through natural biogeochemical processes.

The main challenges for this approach are the space required for reservoirs or infiltration ponds and the infrastructure and pumps to transport the water to the infiltration ponds, and that a significant treatment might be required to make surface water suitable for infiltration and consumption. Another concern is the impact on the environment. This can be not only positive as combating desiccation but also negative, when flooding occurs due to the increase in groundwater levels (Abboud et al., 2018).

An example of the Water Battery concept is active near the village Epe, in the centre of the largest Dutch nature reserve, de Veluwe, which is an ice-pushed ridge (Figure 4a), where groundwater withdrawal occurs since 1954. Around 5 Mm^3/y is extracted to supply the cities of Vaassen, Epe, Heerde and Wapenveld. Since 2015, water from natural springs flowing to the Klaarbeek and Grift streams is collected in a man-made reservoir downhill, monitored and recirculated. Then, water is pumped uphill to infiltration ponds, where it infiltrates directly above extraction wells. The local water balance (Figure 4c) indicates the extracted volumes which almost equals the infiltrated water (i.e. net-withdraw close to zero). Chapter 4 brings a more detailed example of a potential larger-scale Water Battery in the Netherlands.

Fresh/salt: Flexible extraction within saline/brackish environments

This concept is especially important for coastal areas since it can slow down and minimise impacts of saltwater upconing

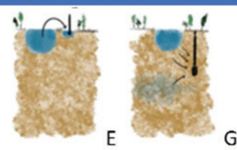
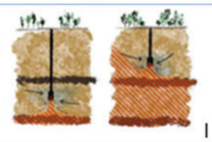
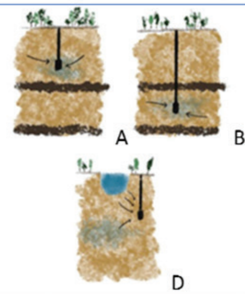
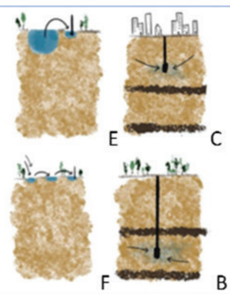
Flexibility concept	Archetype extractions	Flexibility	Resilience to climate change	Scalability	Source Water quality	Cost-Benefit aspects	Positive impact
Water Battery		++	+++	+++	--	+	Providing more water for ecosystems
Fresh/salt		++	++	+	+/-	-	Smaller claim on landscapes (compared to other archetypes)
Switching between abstractions		+	++	-	++	+	Less competition for water with rural areas and ecosystems
Resource city		++	++	++	--	-	More self-sufficient, circular, and green cities

Figure 2. Solution concepts and their link to different archetypes alongside their scores to the different criteria. Scores range from '+++' being the most favourable to '---' being the least favourable. A score of +/- indicates a balance of both favourable and unfavourable attributes. The letters near the figures indicate the archetypes.

and seawater intrusion. Deep extractions wells are far from potential surface contamination sources, but they may be relatively close to the fresh-salt interface. With prolonged extraction and pumping, salinisation of groundwater may occur either laterally (from the seaside) or from deeper units (i.e. upconing). A general action to minimise (or avoid) salinisation is to adjust the extraction strategy plans or switch between extraction points. Several options to do so are illustrated with numbers 1–5 in Figure 5 and described below:

1) Alternating extraction rates through time: interval extraction;
2) Extracting water from multiple wells or horizontal wells, increasing the extraction area: diffuse extraction;
3) Infiltrating fresh water and withdrawing it later through wells: Aquifer Storage and Recover (ASR);
4) Smart wells (fresh-keepers): influencing fresh-salt interface through smart extraction of both fresh and salt (or brackish) water;
5) Brackish water extraction and desalinisation (e.g. for different uses).

Alternating extraction through time or extracting water from different wells would allow the progressing saline front towards the wells to slow down whilst enabling the fresh/salt interface to move away from extraction points. Preconditions for these solution concepts are the possibility to scale up/down the extraction capacity, to construct wells differently (e.g. multifilter sections) or to extract from different wells, increasing the extraction area and reducing local upconing, for instance.

Whilst examples of ASR are observed worldwide (Dragoni & Sukhija, 2008; Fathi et al., 2021; Hiscock et al., 2024; Stefan & Ansems, 2018; Ward et al., 2009), studies have also shown that direct extraction of brackish or saline groundwater from a coastal aquifer can increase aquifer freshening, whilst it also rehabilitates parts that were salinised (Stein et al., 2019). For example, in a recent modelling study, Kassem et al. (2024) suggested that brackish water extraction wells should be situated near the centre-bottom of the intrusion zone. According to the authors, for injection wells, the optimal location would be at the aquifer's bottom and close to the coastal boundary. A precondition for brackish water extraction is technical and

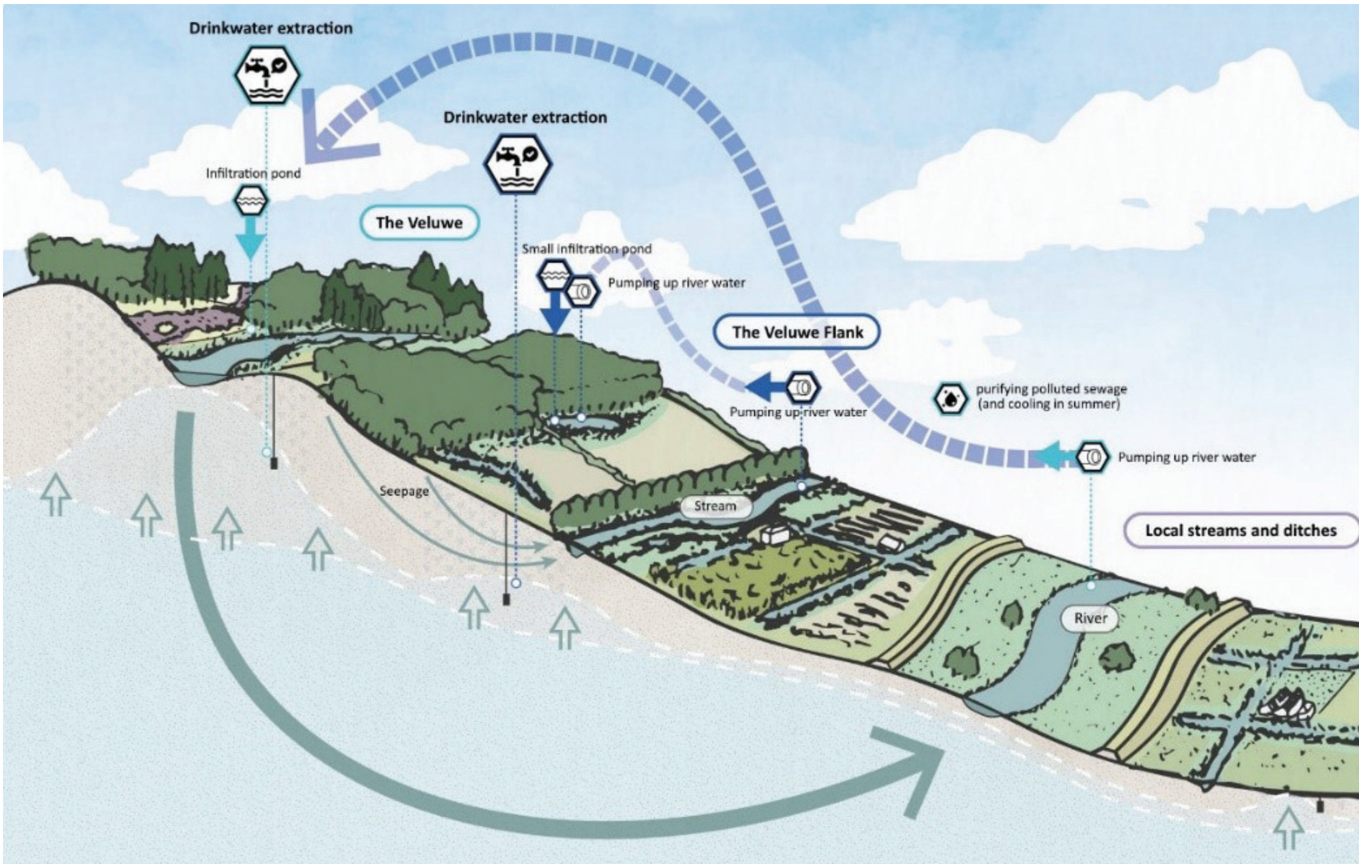


Figure 3. Schematic representation of Water Battery concept for the Epe case (see also: https://specials.deltares.nl/flexibele-drinkwaterwinningen).

financial feasibility, as well as a solution for the residual product (brine). The COASTAR project (www.coastar.nl/) and the FRESHMAN pilot-study (www.dunea.nl/algemeen/life-freshman) are some of the examples of this solution concept implemented in the Netherlands.

Switching between extractions: increasing flexibility for water supply

This concept relies on the idea that GW can be withdrawn from different locations in the area or different depths in the aquifer at different times of the year, which can minimise large drawdowns. By switching between extraction sites, more water can be extracted with reduced impact on the environment. Three possible approaches can be envisaged, which are illustrated in Figure 6:

1) Vertical switching: between deep and shallow extraction points;
2) Switching in time: between a 'summer' and 'winter' extraction point;
3) Horizontal switching: between one site and another.

Vertical switching in time reduces vulnerability to possible contaminations from the surface and can minimise impacts to shallow phreatic systems during periods of water deficits. This approach is suitable at locations where an aquitard (e.g. clayey unit) between a shallow and deeper aquifer is present. Switching over time can offer resilience to fluctuations as seasonal variation in water demand. For example, at Zoelen, in the winter, surplus of water and extractions may have little impact on the environment, whereas in the summer, the available water is under pressure. Extraction rates can be proportionally split to the different locations or aquifers, like in Culemborg (20–80% as the example 2 in Figure 6). However, this does require the ability to build additional infrastructure and may require additional treatments if water of different quality is extracted. By switching between different locations (horizontal switching), different water types can be combined and dilute high concentrations of undesired solutes.

Resource city

The concept of Resource city is gaining relevance in view of accelerated urbanisation and climate change (Hallegatte, 2009; IPCC et al., 2021). Cities should be designed in ways that water extractions form an integral part of them: the water supply can grow flexibly and sustainably along with the water demand (Figure 7). This requires planning in advance, but it brings numerous co-benefits. Due to spacious and green layout required in the Resource City for water infiltration, drinking water production indirectly contributes to biodiversity, health, water storage and combating heat stress. Yet, planning climate adaptation interventions and evaluating their relative impact poses a complex challenge (Mcevoy et al., 2018; van de Ven et al., 2016). The Resource city is based on multiple building blocks that together help it achieve sustainability and

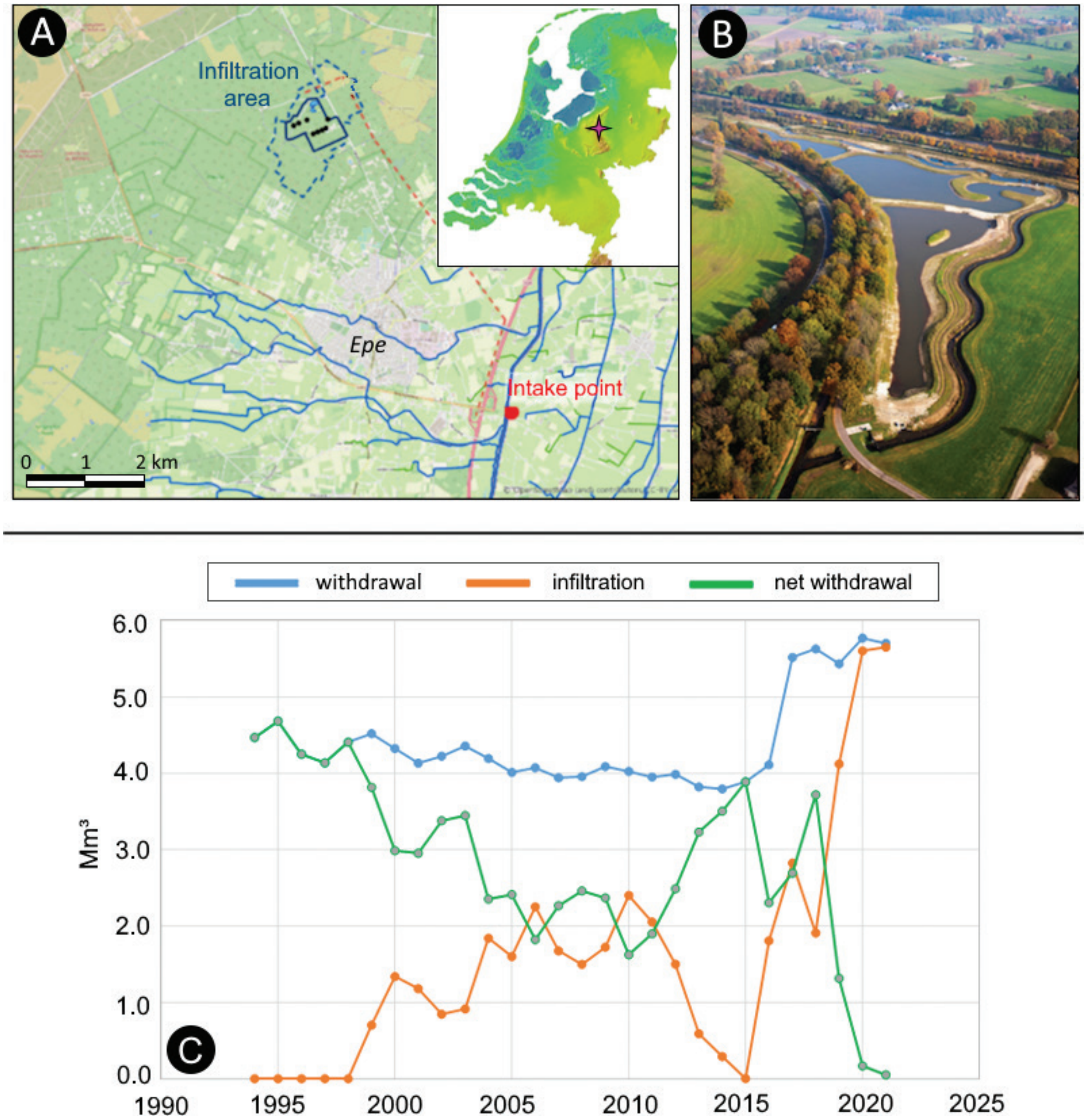


Figure 4. (a) Location of the Epe Water Battery with indication to intake point and infiltration area. The inset map shows its location in the Netherlands (coloured according to surface elevation); (b) collection basin downhill; and (c) water balance for Epe Water Battery: a net-withdraw close to zero indicates that most of water exploited from the aquifer comes from infiltrated water.

ensure that there is always enough clean water. These blocks are:

1) savings/circularity: creating awareness about saving and reusing drinking water, as well as limiting activities and historical soil pollution in the city that might have a negative effect on water quality and quantity;
2) surface/rainwater collection: urban open spaces and other approaches to infiltrate and store water. For instance, water from (green) roofs is returned to the system as much as possible;
3) increased infiltration/soil passage/extraction cone: water infiltrates through soil long enough before it enters abstraction cones, which ensures sufficient good water quality;
4) ASR: infiltrate (clean) water in aquifers and extract it during periods of high demand or water stress, and reducing effects of extraction from secondary (deeper) aquifers;
5) optional: brackish water extraction: water can be targeted to industries (e.g. cooling water for power generation), which reduces pressure on freshwater resources.

Resource city aims to tapping a new source for extracting drinking water whilst improving the urban water system. For this, explorative tools can be useful instruments to engage stakeholders and gain insights into system functioning to explore changes in the landscape that could increase water resilience of cities and surroundings (McEvoy et al., 2020). Tools such as the Risk Stress Test tool (www.worldbank.org/en/topic/climatechange/brief/risk-stress-test-tool, World Bank, 2021) or the Climate Resilient Cities (CRC) tool (crctool.org/en, Deltares, 2022) can be used with multiple stakeholders in workshop settings to quickly explore and compare adaptation options for an area. For instance, the CRC tool is based on the Adaptation Planning Support Toolbox (van de Ven et al., 2016), and it has been applied in diverse cities (e.g. Amsterdam,

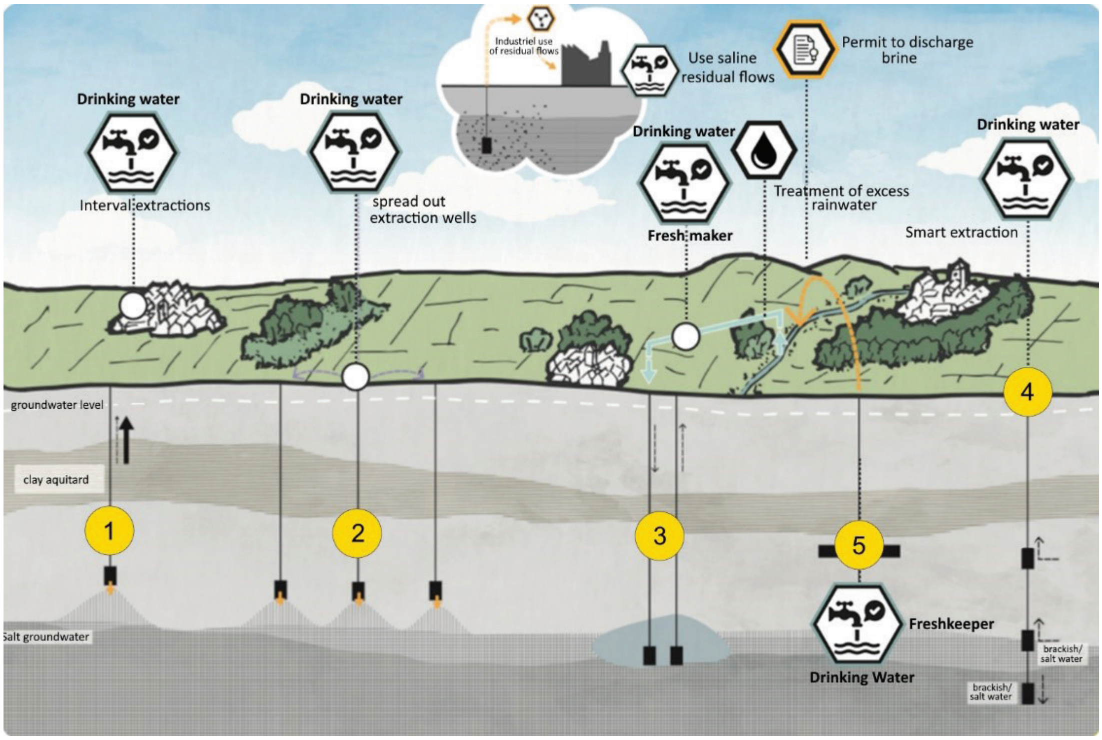


Figure 5. Schematic representation of fresh/salt: solutions to make extractions more flexible against salinisation (see also: https://specials.deltares.nl/flexibele-drinkwaterwinningen).

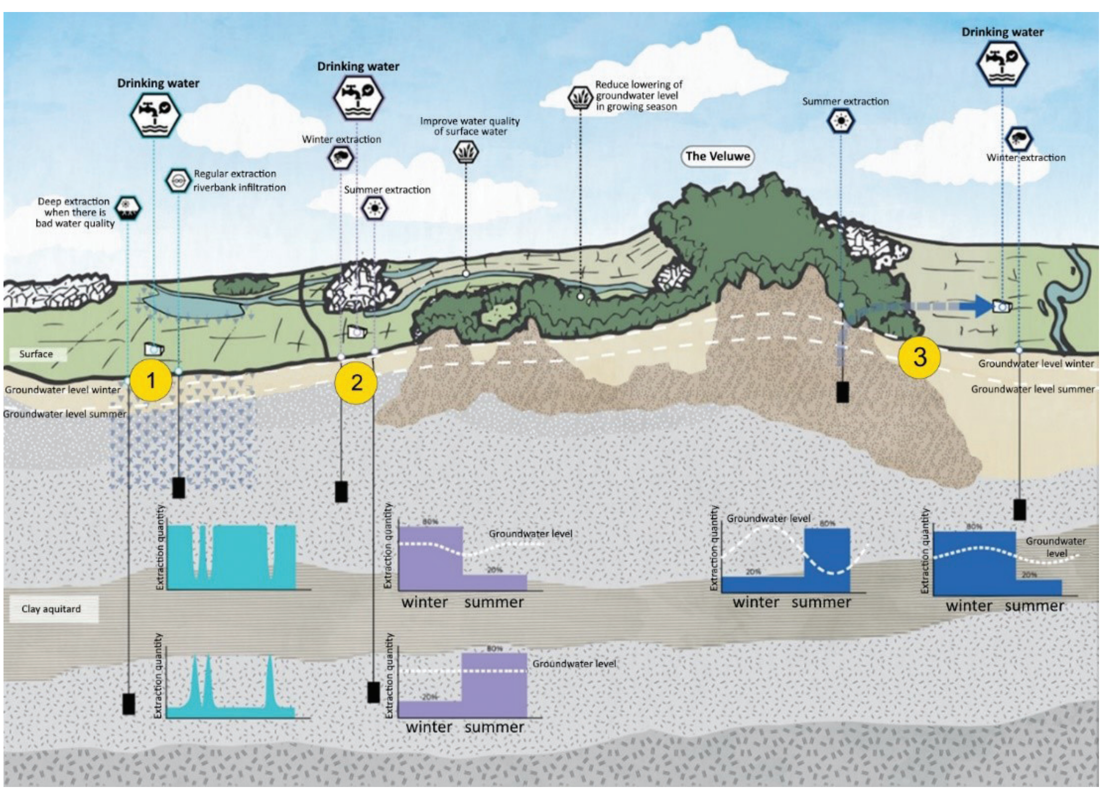


Figure 6. Schematic representation of switching between extractions (see also: https://specials.deltares.nl/flexibele-drinkwaterwinningen).

Berlin, New Orleans, Quayaquil, Antananarivo and Xiangtan amongst others) to assess effects of different nature-based solutions and hybrid measures within cities' landscapes on the urban water balance, stormwater capture, associated costs, heat stress and other co-benefits (McEvoy et al., 2020). This and other similar tools can support the decision-making process

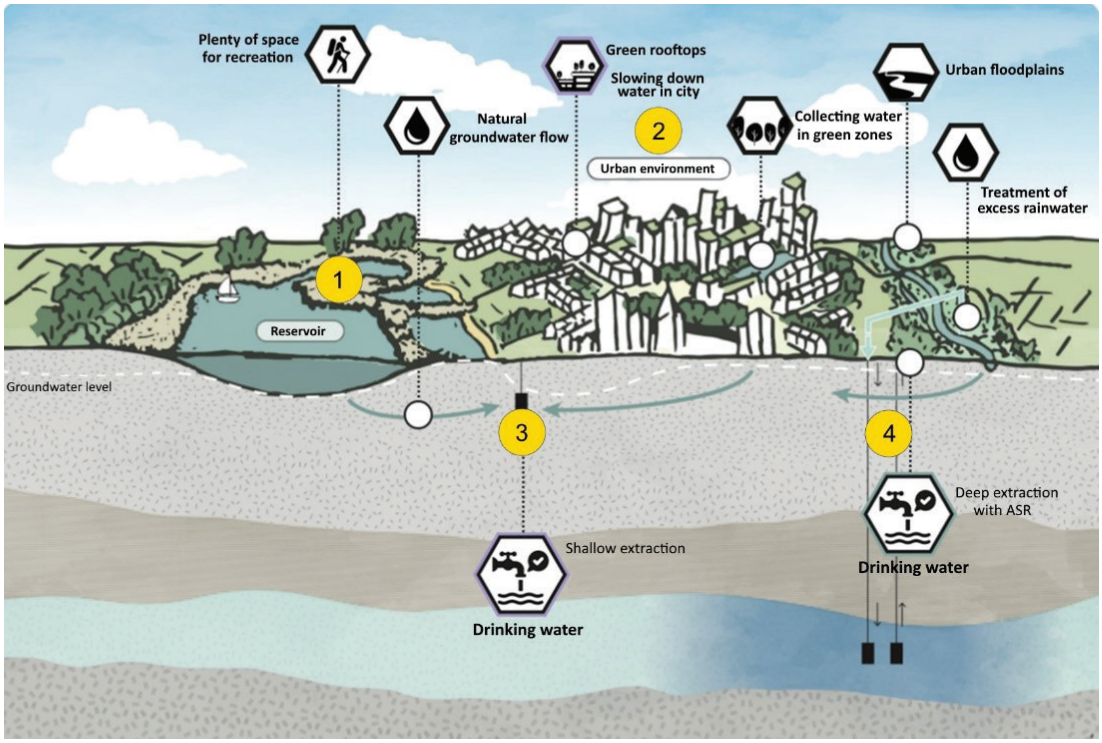


Figure 7. Schematic representation of Source City (see also: https://specials.deltares.nl/flexibele-drinkwaterwinningen).

and the selection of solutions for detailed feasibility studies. Such systematic evaluations can greatly help with urban adaptation plannings, including drinking water production.

Suitability maps of different solutions

Based on pre-requisites for the solution concepts described, we have assessed their most suitable locations in the Netherlands (Figure 8). It is noteworthy that for many locations, more than one concept is viable, which further increases flexibility by providing choices between solutions concept for local extraction archetypes. However, there are also locations where none of the solution concepts could be implemented. Details on how the areas were calculated can be found in the supplementary material.

The suitable locations where water batteries could be implemented in the Netherlands depend on space in the unsaturated zone above the groundwater level. Therefore, areas with relatively deep groundwater levels (minimum of 2.5m from surface level) and a mean difference of 5 m between mean high and low groundwater levels are suitable. Areas showing shallow clay layers were excluded (e.g. low infiltration capacity), leading to approximately 8% of the total territory. Considering that the Resource Cities solution concept is most promising in large- and medium-sized cities (more opportunities to store urban water underground for later extraction), between 4 and 8% of the Netherlands would be suitable for it.

On the other hand, more than 25% of the total area of the Netherlands would be suitable to implement Fresh/Salt concepts. However, in the west and northwest of the Netherlands, sea level rise decreases the suitability due to increased risk of lateral salinisation (yellow hatched areas in the map), which reduces the suitability. About 15% of the country would be also suitable for brackish water extraction.

Switching between extractions locations in time is most promising in low (mostly level-controlled) and higher (free-draining) areas, representing roughly between 5 and 15% of the total area of the country. A precondition for the vertical switching between shallow and deep extractions is the presence of a sufficiently thick clay layer between aquifers, resulting in approximately 20–30% of the country. To the west of the country, the presence of highly brackish/saline water limits the application of the concept.

The Veluwe Water Battery study-case

Like most MAR techniques, the Water Battery (WaBt) concept requires capacity in the subsurface to store infiltrated water (i.e. sufficiently deep groundwater levels) and suitable soil types for infiltration. Besides this, the elevated area should be wide enough to prevent fast drainage of the infiltrated water. One such location in the Netherlands is the Veluwe (Figure 8a), a centrally located higher lying ice-pushed ridge and nature-conservation area, without active drainages and deep groundwater levels (5 to 60 metre below surface level).

De Louw et al. (2020) explored the WaBt potential of the area considering two infiltration options: 100 mm/d and 1000 mm/d using small and large infiltration ponds, respectively. Overall, their results indicated that more but smaller infiltration ponds give longer retention time, with up to 23% of infiltrated water retained 10 years after infiltration has started. Another advantage of the smaller ponds is the less space required for the infiltration (and for other water supply infrastructure). The scenario with large infiltration ponds raised GW levels to 28

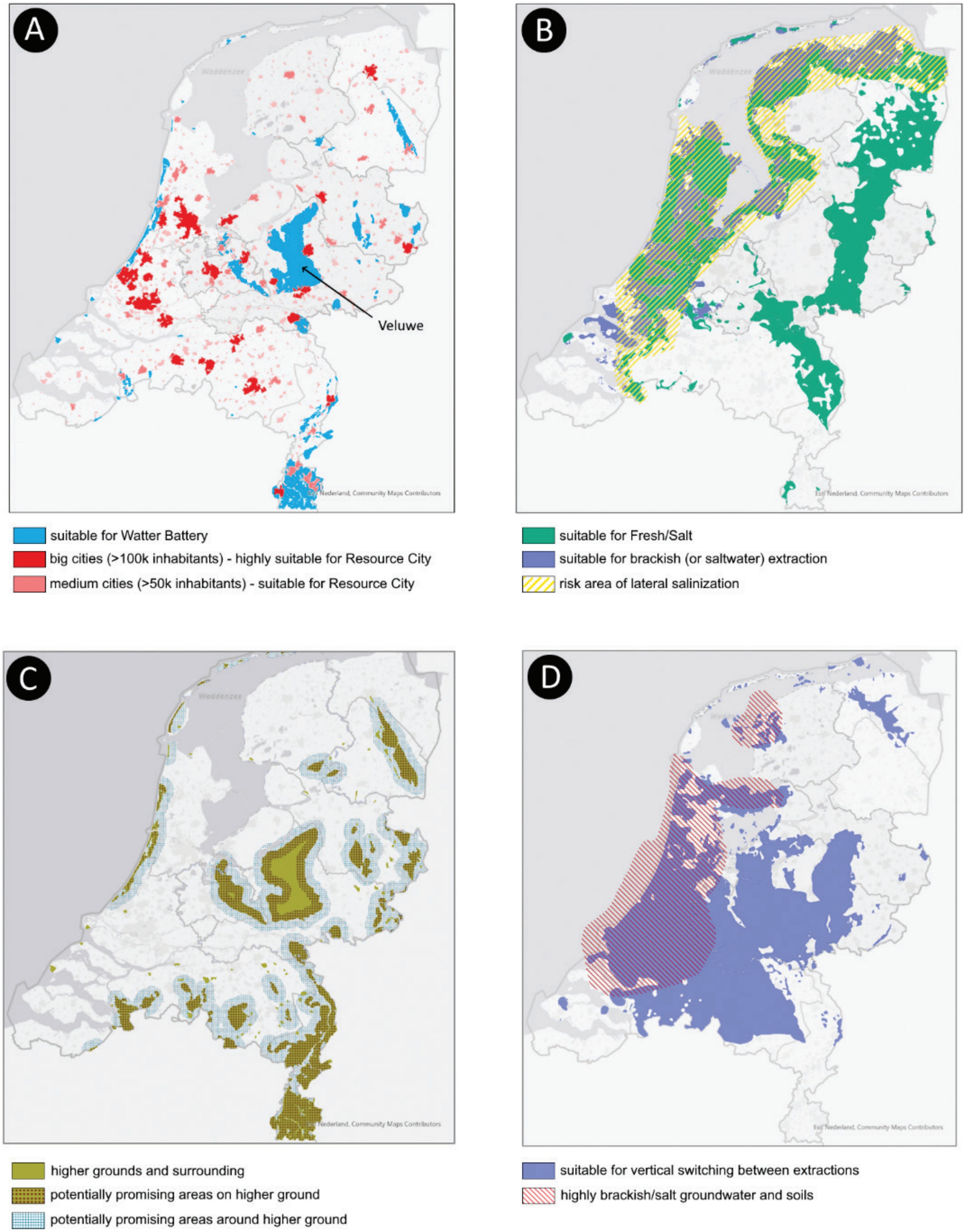


Figure 8. Suitable locations for different solution concepts in the Netherlands according to their pre-requisites: (a) Water Battery and Resource City; (b) Fresh/Salt; (c) Switching between extraction (horizontally); and (d) Switching between extraction (vertically). More than one concept could be applied to different locations (see also: https://specials.deltares.nl/flexibele-drinkwaterwinningen). The Veluwe area is indicated in figure (a).

Table 1. Characteristics of infiltration and extractions in simulated scenarios (A-E)

	A	B	C	D	E
Infiltration (Mm³/y)	50	100	100	100	200
Infiltration locations	3	3	3	2	2
Infiltration period	All year	All year	All year	Nov – April	Nov – April
Extraction volume (Mm³/y)	-	50	50	50	100
Extraction locations	-	6 new locations	11 existing locations	2 × 4 locations around infiltration	2 × 4 locations around infiltration
Simulation period (years)	10	10	10	30	30

metres from original values, causing large hydraulic gradients and resulting in faster flow towards the flanks of the Veluwe plateau, and therefore bigger losses (only 5% of the water was retained after 10 years).

Since the WaBt is mostly useful for the extraction of infiltrated water, we extended their results to include extraction. We carried out additional simulations using the Dutch national groundwater model (LHM, https://nhi.nu/modellen/lhm/) and assessed the performance of the WaBt when extraction takes place. Our model setup followed their exact framework, with changes made only to the extraction wells around the Veluwe area. Briefly:

- the MODFLOW model covers the whole of the Netherlands;
- cell size is 250 × 250 metres;
- eight model layers (varying thicknesses) for subsurface and soil compartments;
- (hydro)geological information acquired from REGIS II dataset (TNO-GDN, 2024);
- model is forced with daily stress-periods from 2008 to 2017 (from 1988 for two cases);

For more detailed information of model setup, we refer to De Louw et al. (2020). We developed five scenarios (A-E) by taking into account actual extraction volumes and hypothesised an increase of this amount alongside the implementation of a WaBt. Scenario A consists only of infiltration as similarly done in De Louw et al. (2020). Scenarios B and C simulate groundwater extraction in two different ways: scenario B assumes new locations, and scenario C uses existing extraction locations in the area. Scenarios D and E are explorative cases with two infiltration ponds (with seasonal infiltration periods) and extraction sites around them, whilst scenario E has double the infiltration capacity of scenario D. For these cases, we simulated 30 years to assess long-term changes in the system. In scenarios with extraction, the infiltration volumes are twice the extracted volumes to assure environmental co-benefits. Table 1 displays the characteristics of the simulations.

The results show that infiltration from WaBt led to a clear rise in GW levels (Figure S2, supplementary material), indicated by positive values and blue areas in Figure 9, whereas extraction led to local lowering of the GW levels (yellow-red areas in Figure 9). In scenarios D and E with abstraction wells closer to the infiltration ponds, the increase in GW levels in the area is less prominent; however, the positive effects are still visible.

With extraction wells closer to the infiltration ponds (scenarios D-E), the effects of extraction are fully compensated by the infiltration even with double the volume extracted. The net added water volume (infiltrated minus extracted volume) causes a permanent groundwater level increase and extra groundwater seepage to local streams, which is favourable for groundwater dependent ecosystems.

As it takes time for the infiltration effects to spread to the flanks, the effects of extraction are dominant in the starting phase, and the rise in stream discharge values is delayed (around 3–4 years for scenarios B and C, Figure 10 and Figure S3, supplementary material). To prevent hindrance and desiccation, it would be strategic to delay GW extraction or locate extraction points differently as in scenarios D and E, for example. In such cases, this effect is not visible since extraction takes place immediately near infiltration ponds. Thus, stream discharge immediately rises with infiltration, and only small seasonal variations are observed due to the seasonal infiltration patterns of these scenarios.

Assessing changes in stream discharge is the only one way to evaluate the WaBt effectiveness, whereas other quantitative assessments (e.g. GW rise vs. infiltration vol., water retention time and water-price) can also be analysed for a clearer understanding of its practical impacts. The absence of drainage locally plays a large role in this approach's success. In most sandy areas of the Netherlands, drainage systems are in place to discharge excess precipitation, which makes water conservation for longer periods very difficult. Increasing the distances between ditches by filling-up watercourses could help drained areas to retain water during winter for the summer. The elevated areas with deep groundwater levels and with large distances to ditches, streams and drainage canals are the most suitable for the Water Battery.

Discussion

Resilience and adaptability of solution concepts

In this study, we presented different solution concepts for increasing flexibility of drinking water production. An overview of advantages and disadvantages to each concept is presented in Table 2.

With climate change, the need for flexible drinking water extraction concepts will become even more important. Sea levels rise enhances salinisation, and predicted hotter and drier summers will lead to lower groundwater levels and reduced river discharges, all reducing the freshwater availability (IPCC et al., 2021). This affects all presented archetypes, but especially shallow and surface water extractions. Furthermore, extracting shallow groundwater in times of drought (or water deficit) may further impact nature. Therefore, implementation of solution concepts and approaches is crucial for these extraction archetypes.

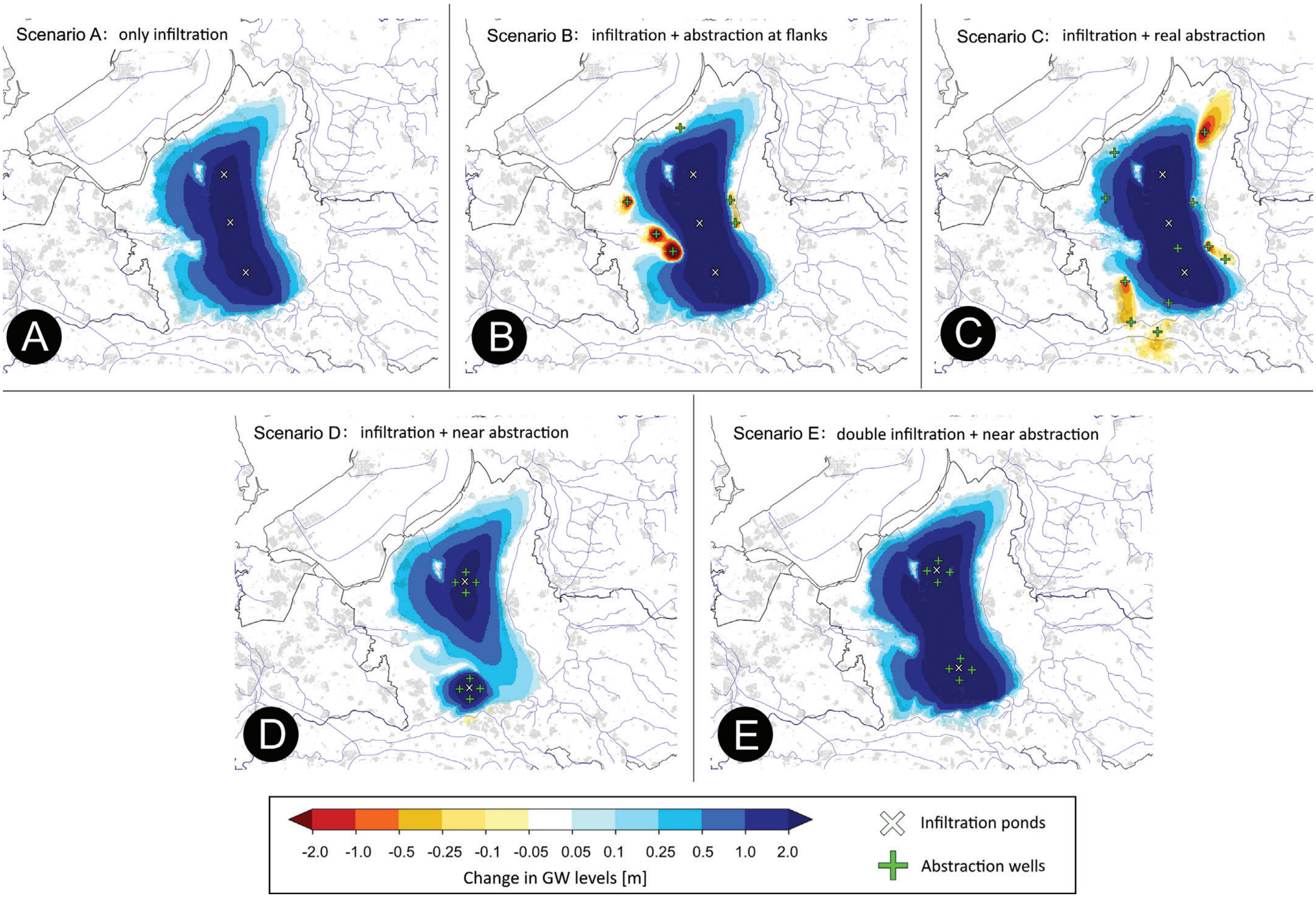


Figure 9. Groundwater level changes (rise in blue and decrease in red) due to infiltration measures and groundwater extraction for scenarios A to C after 10 years (a to c) and after 30 years for scenarios D and E (d and e). White diagonal crosses indicate infiltration ponds, and green vertical crosses indicate GW extraction wells.

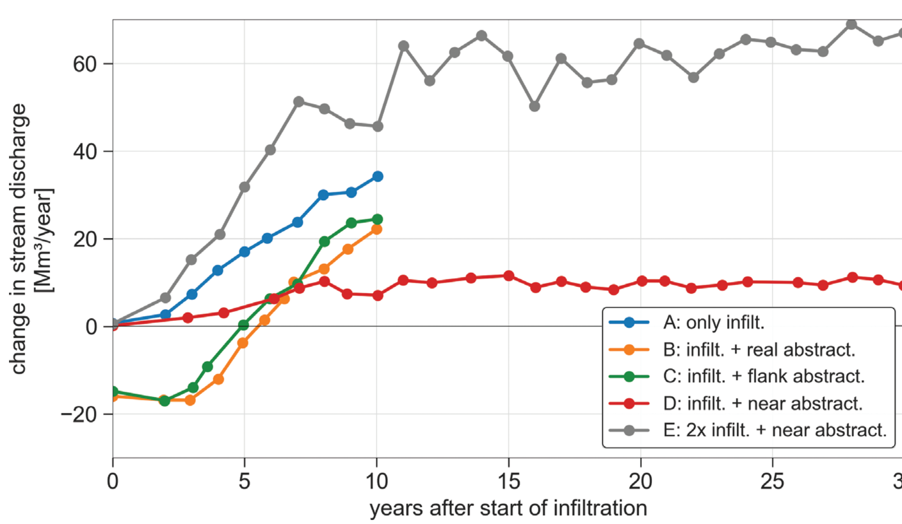


Figure 10. Change in discharge from all simulated streams and springs from base case (no WaBt implemented). Positive values indicate a rise in stream discharge values, whilst negative values indicate decreasing stream discharges. The general rise of values in every scenario is related to additional GW seepage.

A higher sea level will also lead to further salinisation via rivers and deltas, which is a relatively quick process. However, salinisation of deeper aquifers is a comparably slow process (i.e. decades), especially if decentralised extraction and fresh/salt management are planned upfront. Deeper extraction and fresh/salt management can provide short-term and long-term

Table 2. Advantages and disadvantages of solution concepts for flexible drinking water extraction considered in this study

Solution Concept	Advantages	Disadvantages
Water Battery	- Can contribute to flexibility at different areal scales (depending on infiltration area); - Compensates adverse effects of abstractions to ecosystems. - Can lead to more seepage on the flanks and discharge from springs; - Infiltration with strategic placed extraction sites benefits nature due to higher seepage and higher stream discharges.	- The infiltrating water must be of sufficient quality (pre-treatment might be required) - Infiltration of surface water into the groundwater system can also lead to changes in the composition, including macronutrients, of the groundwater; - Site should be near surface waters as source for infiltration, or water must be transported (costly and less sustainable); - Sufficient subsurface infiltration capacity required. - Flooding and hindrance of high groundwater levels requires careful planning and strategic locations of both infiltration and extraction sites.
Fresh/Salt	- Large amounts of water available throughout the year (extra source available); - Deep extractions have less impact from and on the environment; - Deep extractions can replace shallow extractions with more impact.	- With continuous extraction, salinisation is inevitable; - Approaches can be costly due to piping, drilling, treatment and residual flows; - Desalinisation is energy demanding; - For brackish water extraction, technical and financial feasibility and processing of the residual product (brine) are issues to solve; - Increasing pressure on subsurface GW reserves, including energy transition (e.g. geothermal), may compete with drinking water production.
Switching between Extractions	- Great contribution to flexibility; - Resource (type, location and depth) can be switched when water quality is not adequate and to minimise impact on the ecosystems; - By connecting different well fields to one purification plant, it is possible to switch between wells with varying water quality through smart control and leading to less purification effort and costs.	- Technically challenging and requires substantial investments; - Additional infrastructure needed for different extraction points; - Additional treatment might be necessary if water compositions differ too much.
Resource City	- Self-sufficiency: effects on the environment are minimal; - The concept combines well with nature and water storage in the city; - There are already several examples of the concept on a small scale.	- Successful implementation of the concept requires large space, direction and choices; - (Historical) contaminants pose a risk to water quality; - Crowding in the subsurface can be a bottleneck (including from soil energy systems).

flexibility because it is less affected by climate change or land use changes. Implementing and scaling-up extraction concepts for deep GW archetypes are possible, but care should be taken to avoid upconing and further salinisation (Dufour, 2000; van der Gun & Lipponen, 2010).

Despite large amounts of brackish water and its potential for growing salt-tolerant crops, it is still only used in limited amounts (FAO & AWC, 2023). An important question regarding salinisation is which quantities can be extracted without salinisation being a constraint. We must not only control and monitor the withdrawn volumes when demand varies but also know the extent to which the extraction method influences salinisation itself. For example, what is the influence of pumping at different locations or depths compared to extracting at a single point? This and other questions should be considered when implementing this solution concept.

Seasonal switching between extraction, both vertically and horizontally, will ensure sufficient water to be extracted without posing a major environmental impact. The use of multiple extractions (e.g. decentralised) provides resilience and can help in dealing with more dynamic fluctuations expected with climate change (Leigh & Lee, 2019). However, this requires commitment and investment in infrastructure as well as environmental and hydrogeological studies. Finally, MAR with seasonal infiltration and recovery periods (e.g. Water Battery) can ensure that sufficient water can always be extracted with minor impact to the local environment.

Legal and operational framework

Although the solutions described offer a series of benefits (optimising drinking water supply, minimising ecological impact and others) acknowledged by water resources specialists, their implementation is still modest in the Netherlands and worldwide (Jakeman et al., 2016). One of the main reasons for this is the lack of awareness and access to information (e.g. pilot-studies and projects). Thus, water supply operators often adopt solutions with which they are more familiar, but which might be more costly and less effective (Seidl et al., 2024; Sheehan, 2009). Better dissemination of successful projects could help stakeholders to understand the benefits. Next to this, legal and operational limitations might hamper implementation. Future changes in the Netherlands may have implications for the applicability of solution concepts. New homes, nature restoration, vitalisation of rural areas and energy transition unavoidably need space. Not only here but also globally, spatial planning will need even more coordination and synergy amongst users and regulators in the coming decades, which has implications for drinking water production. Water demand will increase depending on new residential development sites, and further urbanisation may put pressure on water quality; or, on the contrary, extraction sites may be secured through greater protection of space and nature whilst integrated into the urban and natural landscape (Damon, 2024; McEvoy et al., 2020).

Regulatory approvals can significantly slowdown the implementation process, for example, Dutch regulation for the Water Battery concept depend on the water source used for infiltration: surface water, treated effluent, or treated urban wastewater. However, there are not yet any known quality requirements (environmental standards) that the purified effluent to be infiltrated must meet. For switching between extractions, flexible permits (with seasonal limits, for instance) are required, which are not yet common, whilst fresh/salt concepts require permits to discharge salts into the environment. Resource cities may require cost internalisation to bear the costs of managing and cleaning-up polluted soils, rather than shifting the burden to taxpayers or society.

On the other hand, a clear regulatory framework can help take away barriers and increase acceptance (Kloosterman et al., 2022). For example, in Belgium, newly built residencies are legally obliged to include rainwater infiltration. Another example is water quality regulations for water infiltration. In the Netherlands, these are addressed in the Infiltration Decre (Infltratiebesluit) (which merged into the Omgevingswet since January 1st, 2024). This gives some legal framework and an initial way forward. However, in practice, the complexity of the groundwater system and worries over potential issues pose a barrier for implementation. Gaining confidence and experience from practical pilot studies can help.

Finally, flexible water source concepts are designed to have positive impacts on overall water resource management and water quality. 'No-regret decisions' refer to choices that have benefits under a wide range of future scenarios and uncertainties. Improving the water quality of both surface water and groundwater can be considered as such a decision because producing high-quality water is extremely challenging despite having advanced treatment technologies available. On top of that, such concepts not only will contribute for flexibility and sustainability in drinking water production but have also implications that extend beyond and go along other critical global transitions (e.g. the 2030 Sustainable Development Goals, *SDG6*: Clean Water and Sanitation, *SDG11*: Sustainable Cities and Communities and *SDG13*: Climate Action).

Whilst we have explored solution concepts that ultimately increase water availability, we were restricted on discussing their implementation costs, optimisation and more thoroughly assessing specific bottlenecks and (socio-economic) opportunities for their development. Thus, future studies could focus on the expansion of concepts under these specific angles. Moreover, research could explore how such solutions could be implemented more broadly also in other regions, examining economic feasibility, technical scalability and environmental impacts. Also, to better support decision-making in urban and regional planning, studies could focus on refining multi-criteria decision analysis (MCDA) tools tailored to the water supply context (Malczewski & Rinner, 2015). These tools could facilitate the evaluation of various water supply solutions, balancing factors like ecological impact, cost, scalability and adaptability in diverse settings (Fathi et al., 2021). Finally, implementing extended monitoring programs on pilot projects, such as the Epe Water Battery, would be beneficial. Future research could focus on the long-term environmental effects, operational efficiency and resilience of solutions under changing climate conditions and increasing water demand (Ward et al., 2009).

Conclusions

Within this study, we discussed solution concepts for increasing flexibility in drinking water production, advantages and disadvantages, effects on water quantity, quality and environment, and some of the knowledge gaps. More flexibility is needed since climate change and increasing water demands are putting more pressure on the freshwater availability, and to reduce impact on the environment as groundwater dependent ecosystems. This provides a basis for further development into practice, whilst parts of the presented solutions are not yet fully demonstrated or proven to be economically viable (or scaled up). Pilot projects and studies as the ones carried out in the dune region and in the Veluwe region and others worldwide show promising results for a sustainable and flexible drinking water production. This not only brings important evidence about the application of the solution concepts but also indicates the need of assessing how to scale-up and transfer such knowledges to other locations in the Netherlands and worldwide.

Successful implementation of these concepts in the Dutch context will go together with complex stakeholder relationships and dependencies, thus requiring negotiation, collaboration and consensus-building efforts. To be prepared for the future, the Dutch will need to adopt a more proactive mindset before reaching a critical point, emphasising action over excessive attention to detail in legislation and regulations. This will require considerable future work to better understand and incorporate into water-science policy discussions.

The concepts are carefully crafted and optimised for their positive impact, but making them effective depends a lot on dealing with challenges. Simultaneously, by prioritising actions that contribute to improving water quality across different sources, water managers and policymakers can make strategic investments that yield long-term benefits and resilience in the face of changing environmental conditions and emerging challenges. Finally, planning tools, modelling studies and field experiments will play important roles in shaping the Dutch water transition. Together with rising awareness and joint commitments (and investments) from different stakeholders, drinking water production can keep up with global changes whilst ensuring sustainability for the years to come.

Acknowledgements

The authors thank TKI Deltatechnologie, Vitens NV and the Deltares strategic research for providing funding for this study (Flexibiliteit in winningen – de oplossing om in te spelen op opgaven van de toekomst, DEL113). The authors would like also to thank Ruimtevolk for collaboration in the spatial visualisation and design of flexible solutions, and more than 25 professionals who reflected their knowledge and expertise, covering all aspects of water science, management and conservation to improve the solution concepts.

References

Abboud, J.M., Ryan, M.C. & Osborn, G.D., 2018. Groundwater flooding in a river-connected alluvial aquifer. Journal of Flood Risk Management **11**(4): 1–11. DOI: 10.1111/jfr3.12334.

Calverley, C.M. & Walther, S.C., 2022. Drought, water management, and social equity: analyzing Cape Town, South Africa's water crisis. Frontiers in Water **4**:910149, 21. DOI: 10.3389/frwa.2022.910149.

CBS (Centraal Bureau voor de Statistiek), 2020a. Population in the future https://www.cbs.nl/en-gb/visualisations/dashboard-population/population-dynamics/population-in-the-future.

CBS (Centraal Bureau voor de Statistiek), 2020b. Netherlands in numbers. https://longreads.cbs.nl/nederland-in-cijfers-2020/hoe-wordt-de-nederlandse-bodem-gebruikt/.

Damon, B., 2024. Nature-based solutions for living systems: connectivity, complexity, community. Nature-Based Solutions **6**: 100136, ISSN 2772-4115. DOI: 10.1016/j.nbsj.2024.100136.

de Louw, P.G.B., 2013. Saline seepage in deltaic areas: Preferential groundwater discharge through boils and interactions between thin rainwater lenses and upward saline seepage. PhD-Thesis – Research external, graduation internal, Vrije Universiteit Amsterdam.

Delsman, J.R., 2015. Saline groundwater - surface water interaction in coastal lowlands. PhD-Thesis – Research external, graduation internal, Vrije Universiteit Amsterdam. IOS Press BV. DOI: 10.3233/978-1-61499-518-0-i.

De Louw, P., Peters, J., Kaandorp, V. & Oost, A., 2020. Verkennend rekenen aan grootschalige infiltratie op de Veluwe. H2O: tijdschrift voor watervoorziening en afvalwaterbehandeling, 53, 38–40. https://www.h2owater-netwerk.nl/images/2020/Mei/Infiltratie_Veluwe_H2O_Online_.pdf.

Dragoni, W. & Sukhija, B.S., 2008. Climate change and groundwater. In Special Publication 288 (Vol. 54, Issue 2). London: The Geological Society. www.geolsoc.org.uk/bookshop.

Dufour, F.C., 2000. Groundwater in The Netherlands—Facts and Figures. Delft/Utrecht, The Netherlands: Netherlands Institute of Applied Geoscience TNO; p. 96.

DutchNews, June 5th, 2023. https://hydrologicalextremes.org/2023/02/01/dutch-drought-2022-a-perspective-by-the-ivm-drought-risk-research-group/.

FAO & AWC, 2023. Guidelines for brackish water use for agricultural production in the Near East and North Africa region. Cairo: FAO; p. 271. DOI: 10.4060/cc3234en.

Fathi, S., Hagen, J.S., Matanó, A. & Nogueira, G.E.H., 2021. Review of GIS multi-criteria decision analysis for managed aquifer recharge in semi-arid regions. In C.B. Pande & K.N. Moharir (Eds.), Groundwater resources development and planning in the semi-arid region Cham: Springer. DOI: 10.1007/978-3-030-68124-1_2.

Geelen, L.H.W.T., Kamps, P.T.W.J. & Olsthoorn, T.N., 2017. From overexploitation to sustainable use, an overview of 160 years of water extraction in the Amsterdam dunes, the Netherlands. Journal of Coastal Conservation **21**: 657–668. DOI: 10.1007/s11852-016-0452-x.

Gelati, E., Zajac, Z., Ceglar, A., Bassu, S., Bisselink, B., Adamovic, M., Bernhard, J., Malagó, A., Pastori, M., Bouraoui, F. & De Roo, A., 2020. Assessing groundwater irrigation sustainability in the Euro-Mediterranean region with an integrated agro-hydrologic model. Advances in Science and Research **17**: 227–253. DOI: 10.5194/asr-17-227-2020.

Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. Global Environmental Change **19**(2): 240–247, ISSN 0959-3780. DOI: 10.1016/j.gloenvcha.2008.12.003.

Han, M.Y. & Mun, J.S., 2011. Operational data of the Star City rainwater harvesting system and its role as a climate change adaptation and a social influence. Water Science and Technology **63**(12): 2796–2801. DOI: 10.2166/wst.2011.597.

Hiscock, K.M., Balashova, N., Cooper, R.J., Bradford, P., Patrick, J. & Hullis, M., 2024. Developing managed aquifer recharge (MAR) to augment irrigation water resources in the sand and gravel (Crag) aquifer of coastal Suffolk, UK. Journal of Environmental Management **351** (December 2023): 119639. DOI: 10.1016/j.jenvman.2023.119639.

Hofman-Caris, R., Bertelkamp, C., de Waal, L., van den Brand, T., Hofman, J., van der Aa, R. & van der Hoek, J.P., 2019. Rainwater harvesting for drinking water production: a sustainable and cost-effective solution in The Netherlands? Water **11**: 511. DOI: 10.3390/w11030511.

INOWAS, 2018. Innovative Groundwater Solutions. https://www.inowas.com/mar-methods/aquifer-storage-and-recovery-asr/.

IPCC, Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. & Zhou, B., 2021. IPCC, 2021: climate change 2021: the physical science basis. Contribution of Working Group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge and New York, NY: Cambridge University Press. DOI: 10.1017/9781009157896.

Jakeman, A.J., Barreteau, O., Hunt, R.J., Rinaudo, JD. & Ross, A. (eds)., 2016. Integrated groundwater management. Cham: Springer. DOI: 10.1007/978-3-319-23576-9_3.

Kloosterman, R.A., Herder, P.M. & van der Hoek, J.P., 2022. Enhancing the resilience of drinking water infrastructures. International Journal of Critical Infrastructures **18**(4): 336–365. DOI: 10.1504/IJCIS.2022.128095.

KNMI, 2023. Koninklijk Nederlands Meteorologisch Instituut. KNMI'23-klimaatscenario's https://www.knmi.nl/kennis-en-datacentrum/achtergrond/knmi-23-klimaatscenario-s.

Leigh, N.G. & Lee, H., 2019. Sustainable and resilient urban water systems: the role of decentralization and planning. Sustainability **11**(3): 918. DOI: 10.3390/su11030918.

Malczewski, J. & Rinner, C., 2015. Multicriteria decision analysis in geographic information science. New York, NY, USA: Springer; 2015.

Maring, L., van den Meiracker, R., Jansen, S., Kloosterman, R., Niesten, M., Passier, H., Postma, M., Terwisscha van Scheltinga, R., de Vries, S. & Welkers, J., 2022. Flexible drinking water extraction design: solution concepts. Deltares report 11205767-000-BGS-003. https://publications.deltares.nl/11205767_000_0003.pdf.

McEvoy, S., van de Ven, F.H.M., Blind, M.W. & Slinger, J.H., 2018. Planning support tools and their effects in participatory urban adaptation workshops. Journal of Environmental Management **207**: 319–333. DOI: 10.1016/j.jenvman.2017.10.041.

McEvoy, S., van de Ven, F.H.M., Brolsma, R. & Slinger, J.H., 2020. Evaluating a planning support system's use and effects in urban adaptation: an exploratory case study from Berlin, Germany. Sustainability (Switzerland), **12**(1): 173. DOI: 10.3390/SU12010173.

Oude Essink, G.H., 2001. Salt water intrusion in a three-dimensional groundwater system in the Netherlands: a numerical study. Transport in Porous Media **43**: 137–158. DOI: 10.1023/A:1010625913251.

Oude Essink, G.H.P., Van Baaren, E.S. & De Louw, P.G.B., 2010. Effects of climate change on coastal groundwater systems: a modeling study in the Netherlands. Water Resources Research **46**(10): 1–16. DOI: 10.1029/2009WR008719.

PBL, 2014. Planbureau voor de Leefomgeving, Waterkwaliteit en -veiligheid. Balans van de Leefomgeving 2014 – Deel 6, Den Haag. https://www.pbl.nl/publicaties/balans-van-de-leefomgeving-2014.

RIVM (Rijksinstituut voor Volksgezondheid en Milieu), 2018. Quality of drinking water https://www.rivm.nl/en/soil-and-water/drinking-water/quality-of-drinking-water.

RIWA-Meuse (Vereniging van Rivierwaterbedrijven-Meuse), 2023. Annual Report 2022. https://www.riwa-maas.org/wp-content/uploads/2023/09/IDF3064-RIWA-MAAS-Jaarrapport-UK-2022-digitaal.pdf.

Scheierling, S.M. & Tréguer, D.O., 2018. Beyond crop per drop: assessing agricultural water productivity and efficiency in a maturing water economy. Washington, DC: World Bank.

Seidl, C., Wheeler, S.A. & Page, C., 2024. Understanding the global success criteria for managed aquifer recharge schemes, Journal of Hydrology **628**: 130469, ISSN 0022-1694. DOI: 10.1016/j.jhydrol.2023.130469.

Sheehan, L., 2009. Summary of costs and benefits of water supply alter- natives (Report). Sacramento, CA: California Coastkeeper Alliance.

Stefan, C. & Ansems, N., 2018. Web-based global inventory of managed aquifer recharge applications. Sustainable Water Resources Management **4**(2): 153–162. DOI: 10.1007/s40899-017-0212-6.

Stein, S., Yechieli, Y., Shalev, E., Kasher, R. & Sivan, O., 2019. The effect of pumping saline groundwater for desalination on the fresh–saline water interface dynamics. Water Research **156**: 46–57. DOI: 10.1016/j.watres.2019.03.003.

TNO-GDN, 2024. BRO REGIS II v2.2.2. TNO – Geological Survey of the Netherlands, https://www.dinoloket.nl/en/subsurface-models/map.

Toreti, A., Bavera, D., Acosta Navarro, J., Arias-Muñoz, C., Avanzi, F., Marinho Ferreira Barbosa, P., De Jager, A., Di Ciollo, C., Ferraris, L., Fioravanti, G., Gabellani, S., Grimaldi, S., Hrast Essenfelder, A., Isabellon, M., Jonas, T., Maetens, W., Magni, D., Masante, D., Mazzeschi, M., … Spinoni, J., **2023.** Drought in Europe March 2023, EUR 31448 EN. Luxembourg: Publications Office of the European Union. JRC133025. ISBN 978-92-68-01068-6. DOI: 10.2760/998985.

UNESCO, 2023. The United Nations World Water Development Report 2023. In Handbook of water purity and quality. Paris: UNESCO.

van der Gun, J. & Lipponen, A., 2010. Reconciling groundwater storage depletion due to pumping with sustainability. Sustainability **2**(11): 3418–3435. DOI: 10.3390/su2113418.

van de Ven, F.H.M., Snep, R.P.H., Koole, S., Brolsma, R., van der Brugge, R., Spijker, J. & Vergroesen, T., 2016. Adaptation Planning Support Toolbox: measurable performance information based tools for co-creation of resilient, ecosystem-based urban plans with urban designers, decision-makers and stakeholders. Environmental Science and Policy **66**: 427–436. DOI: 10.1016/j.envsci.2016.06.010.

Wang, H., Mei, C., Liu, J. & Shao, W., 2018. A new strategy for integrated urban water management in China: Sponge city. Science China Technological Sciences **61**: 317–329. DOI: 10.1007/s11431-017-9170-5.

Ward, J.D., Simmons, C.T. & Dillon, P.J., 2009. Integrated assessment of lateral flow, density effects and dispersion in aquifer storage and recovery. Journal of Hydrology **370**: 83–99. DOI: 10.1016/J.JHYDROL.2009.02.055

Werner, A.D., Bakker, M., Post, V.E.A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C.T. & Barry, D.A., 2013. Seawater intrusion processes, investigation and management: recent advances and future challenges. Advances in Water Resources **51**: 3–26. DOI: 10.1016/j.advwatres.2012.03.004.

WFD (Water Framework Directive), 2000. 2000/60/EC: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000. https://www.eea.europa.eu/policy-documents/water-framework-directive-wfd-2000.

Winpenny, J., 1997. Demand management for efficient and equitable use. In M. Kay, T. Franks & L. Smith (Eds.), Water: economics, management and demand (pp. 296–303). London, UK: E & FN Spon.