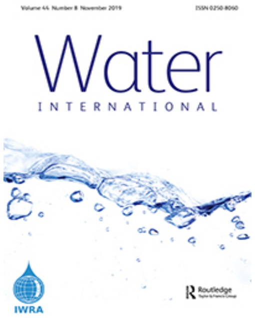

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M. J. Nikkels, P. R. van Oel, H. Meinke & P. J. G. J. Hellegers

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Challenges in assessing the regional feasibility of local water storage

M. J. Nikkels[a,b,c], P. R. van Oel[a], H. Meinke[b,d] and P. J. G. J. Hellegers[a]

[a]Water Resources Management Group, Wageningen University, the Netherlands; [b]Tasmanian Institute of Agriculture, University of Tasmania, Hobart, Australia; [c]Aequator Groen & Ruimte, Harderwijk, the Netherlands; [d]Centre for Crop Systems Analysis, Wageningen University, the Netherlands

ABSTRACT
The regional effects of local water storage are largely unknown. This study identifies, categorizes and discusses the challenges in assessing the potential of local water storage. These are illustrated using a structured method applied to a Dutch case. We conclude that the focus must shift from storage 'potential' (the quantity of water that can be stored) to storage 'feasibility', which depends on exploitability, purpose and interactions between storage alternatives. Spatial and temporal scale also influence feasibility. Finally, farmers' investment preferences are a factor, though these are shrouded in uncertainty. This overview is a first step towards improving storage assessment tools and processes.

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Local water storage; agricultural water management; storage feasibility; scale issues; Netherlands

Introduction

Water shortage is a key constraint on food production in many countries (de Fraiture et al., 2007). This may worsen as climate change is expected to further amplify rainfall variability (Dore, 2005; Solomon et al., 2007). Water storage can mitigate water shortages due to rainfall variability. Appropriate water storage techniques can thus contribute to income and food security. Moreover, strengthening farmers' capacity to overcome drought contributes towards Sustainable Development Goals 2, zero hunger (United Nations, 2015), and 6, clean water and sanitation (United Nations, 2018).

Ponds, farm dams, ditches, drainage systems and subsurface aquifers are some of the local water storage techniques that can help farmers overcome temporary water shortages by providing water for irrigation. Yet, the impacts of these local storage options at larger spatial scales are poorly understood, hampering assessments of how farmers (can) contribute to long-term system-level objectives (ZON & DHZ, 2015). To grasp the potential of local storage as a strategy to increase water availability at the water-system level, it is crucial to know what volume of water can be stored and the associated costs.

Thissen et al. (2015) defined a *water system* as a geographic area or region that depends on one or more water sources. Examples are a polder, a catchment or an irrigation scheme. The literature variously describes local storage techniques as 'scattered', 'small', 'fine', 'spatially distributed', 'decentralized', 'on-farm', 'on-field' and 'private' (Blanc, 2014; Fowler, Morden,

CONTACT M. J. Nikkels melle.nikkels@wur.nl

Lowe, & Nathan, 2015; Wisser et al., 2010). Local storage, furthermore, is taken to imply that the water stored is exploitable and regarded as private property (Feeny, Berkes, McCay, & Acheson, 1990). FAO (2003, p. 4) defined exploitable water as 'water for use' or 'manageable water', to be applied for irrigation or to otherwise support crop growth and human activities.

In 2008, van der Zaag and Gupta called for research on the regional effects of local water storage. They conducted an assessment focused on the choice between small and large surface reservoirs as an irrigation water supply strategy. They compared the storage potential of a hypothetical large-scale dam of 50 million cubic metres (MCM) to 2000 on-farm tanks holding 500 m^3 each. According to these authors, the cumulative capacity of local storage systems is non-linear and difficult to predict, which makes choosing between the two strategies problematic. They concluded that for well-informed decision making, we need a better ability to assess and quantify local storage potential and costs at the system level.

This knowledge gap is well known, but difficult to address. The first step to overcome it is to improve tools for assessing the cumulative impact of multiple local storage facilities in a system context. Hence, the objective of this article is to identify and discuss challenges in assessing local water storage techniques at the regional, or system level. We identify and discuss challenges based on a literature review and an examination of a structured water storage assessment method.

Approach

The research approach entails a literature review related to the article of van der Zaag and Gupta (2008) and a critical examination of a structured water storage assessment method applied to a Dutch case. The case shows why it is so hard to assess the potential of local storage techniques, enabling us to unravel some of the specific challenges involved.

Literature review

Our literature review started with the study by van der Zaag and Gupta. We sought out all 32 articles citing their article (as of July 2019) to see how and by whom their call for research on the regional effects of local water storage was answered. Only 20 out of these 32 articles included the term 'small', 'scale' or 'storage' in their title, keywords or abstract, and of these, 10 directly related to the regional impacts of local storages (Table 1).[1] All 10 directly related papers acknowledge some aspects of the challenges in assessing local water storage techniques at the regional or system level but are limited in their contribution towards improved storage assessment tools and processes.

Considering that the shared recommendation of the articles referring to van der Zaag and Gupta is that the regional effects of a set of local storages deserves further research, a statement by van der Zaag and Gupta (p. 11) is still relevant:

> We might have a fairly good idea of what the biophysical, economic, managerial and socio-political impacts are of a large dam with a capacity of, let's say two hundred million cubic meters; yet we do not know the precise impacts of one million small tanks with a storage capacity of two hundred cubic meters each.

Table 1. Conclusions and recommendations for further research in articles referring to the article of van der Zaag and Gupta (2008).

Van Oel et al. (2018) assess the role of large-scale reservoirs in the Jaguaribe basin, Brazil. They demonstrate that the distribution of storage affects the duration and magnitude of droughts, both upstream and downstream. Although the impacts of on-farm storage are not considered in their study, the authors suggest that their assessment could be helpful in comparing the storage potential of large reservoirs with on-farm storages.
Habets et al. (2018) review modelling approaches to assess the hydrologic impacts of small reservoirs. As their focus is on modelling river flow, they relate to water extraction for irrigation as an exogenous factor. These authors address the data needs relating to the water balance of small reservoirs, the losses, such as seepage and evaporation, and the connection to the stream, i.e., catching all or only a part of the river flow. They conclude that lack of data and model simplifications hamper regional impact assessments.
Van Meter et al. (2016) assess the storage potential of rainwater harvesting tanks in India. These authors note the lack of empirical studies quantifying water fluxes, especially at the regional level. Local storage should not be evaluated in isolation, they observe, as tanks' position in the cascade strongly affects main water fluxes, usability and socio-hydrologic dynamics. (*Socio-hydrologic dynamics* was defined by Sivapalan, Savenije, and Blöschl [2012] as the interactions between water and water users.)
Lasage and Verburg (2015) present a decision framework for selecting water-harvesting techniques. They observe that evaluation criteria, downstream consequences and the socio-economic impacts of water-harvesting techniques are not well described in previous studies. They recommend that agencies and donors consider the impacts on livelihoods and the likely benefits of water-harvesting techniques before advancing agricultural development and conclude that more knowledge is needed on the downstream effects of cascading structures, to evaluate their sustainability and applicability.
Wutich et al. (2014) explore how socio-economic and environmental conditions shape people's perspectives, and preference for strategies to improve the water system. They find that preferences for hard-path solutions (large scale, centralized infrastructure) versus soft-path solutions (decentralized infrastructure and reforming of institutions) are influenced by people's development status and perception of water scarcity. They recommend that future research focus on ambiguities and people's perceptions in decision-making processes.
McCartney et al. (2013) develop a tool to assess four different storage options: large reservoirs, smaller ponds or tanks, groundwater and water stored as soil moisture. They stress that these storage options have distinct social and economic implications and differ in their reliability, resilience and vulnerability. As the authors acknowledge, their assessment of the effectiveness of ponds or tanks does not capture the cumulative effect of distributed, small-scale water storage in their case-study applications in the Volta and Blue Nile basins in Ethiopia. They therefore call for further research on complementarities between different storage options and a focus on economic feasibility.
Lasage et al. (2013) evaluate the downstream effects of sand dams under conditions of climate change in the Dawa catchment in Ethiopia. In their case study, additional sand dams lead to modest changes in downstream flows, but projected climate change and their maximum storage scenario case can extend the duration of low-flow months by 50%. The authors indicate that their assessment contains assumptions and uncertainties but stress that a management strategy to build small-scale structures can easily be adjusted as the future unfolds and so enables learning by doing.
Devineni et al. (2013) introduce spatially distributed indices for water stress. The indices reflect the deficit in a regional water balance and recommend accounting for variability within and between years. They suggest that for large deficits large surface storages are needed, as small storages require a large fraction of arable land, and they recommend extending their approach by including interactions between surface and groundwater.
(Pandey et al., 2011) estimate seepage and evaporation losses of on-farm storages in two locations in Texas (US) and West Bengal (India), concluding that shape, size and soil type of reservoirs are critical factors. They recommend embedding their model in a river-scale model to assess downstream impacts. Seepage losses and evaporation reduce local water availability during the growing season, but interaction with the water system was outside their scope. The authors also compare the cost and benefits of a distributed and a centralized system. They find that the cost/benefit ratio of many local storages exceeds that of a large reservoir but acknowledge that changing the assumed construction costs, size, material and water availability may alter their finding.
Thomas et al. (2011) review the literature on water storage options to sustain low flows in small catchments. The options include artificial groundwater recharge, surface water storage, wetlands and reuse of treated wastewater. They find that these options differ in effectiveness, downstream influence and controllability. They stress the need for further research, specifically on synergies between flood protection and low-flow augmentation, and incorporating climatic and anthropogenic changes.

Obtaining a clear overview of the main challenges in assessing the regional-level impact of local water storage is an important first step towards improved storage assessment tools and processes that aim to inform farmers, water managers and policy makers.

The fresh water options optimizer (FWOO) method

The FWOO method, described by Hoogvliet et al. (2014), seeks to calculate how much freshwater can physically be stored in a particular region using a given set of storage techniques. Hoogvliet et al. selected seven storage techniques (Table 2) from the Dutch applied research programme Knowledge for Climate (www.knowledgeforclimate.nl/programme). With these techniques, water is stored underground and in ditches instead of using productive surface space.

The FWOO method asks two questions: 'Where can a certain technique be applied?' and 'What is the regional water storage potential of a set of local techniques?' This is complemented by a cost-effectiveness analysis (Nikkels et al., 2015). The method has six steps:

(1) Analysis of water shortage
(2) Mapping of physical suitability
(3) Assessment of the impacts of measures on (saline) upward groundwater flows, groundwater and surface water
(4) Assessment of the interaction between local techniques and the adjacent water system
(5) Estimation of the maximum storage potential
(6) Estimation of the water storage potential in the region.

The water management context and case study

The Netherlands sometimes experiences shortages of water quantity and/or quality (Ministry of Infrastructure and Environment & Ministry of Economic Affairs [MIE & MEA], 2014).

Table 2. Local water storage techniques assessed using the fresh water options optimizer method, ordered by storage capacity.

Local storage technique	Description	Change in water lens (m)	Storage capacity (m^3/ha)
Aquifer storage and recovery (coastal)	Captures rainwater aboveground, using a vertical tube for it to slowly infiltrate salty groundwater. Freshwater is withdrawn from various depths to optimize recovery rates.	1.4	4,200
Freshmaker	Expands an existing shallow freshwater lens by infiltration of freshwater through a horizontal tube. An underlying tube withdraws salty groundwater.	0.66	2,000
Creek ridge infiltration	Enlarges a freshwater lens by raising the groundwater level by controlled drainage combined with infiltration of surface water.	0.5	1,500
Drains2Buffer	Deepens controlled drainage so that saline groundwater is discharged to surrounding ditches and the freshwater lens can grow with precipitation.	0.3	900
Controlled drainage	Allows the base drainage level to be adjusted throughout the year, providing the possibility of raising the groundwater level to store water.	0.3	300
Water conservation with small weirs	Raises water levels in ditches, producing a larger buffer in surface water, but also raises the groundwater level in the surroundings.	0.2	200
Water conservation with ditch-bottom elevation	By elevating a ditch bottom, groundwater levels in the surrounding area are raised while maintaining the same quantity of surface water.	0.15	150

Source: adapted from Nikkels et al. (2015, Table 1).

Availability of freshwater may be reduced further in the future, due to foreseen and unforeseen changes in supply and demand (Van Alphen, 2016). Climate simulations indicate that the agricultural sector could face losses of some €700 million every other year if the recurrence interval of dry years shortens from the current one in 10 years to one in two years (MIE & MEA, 2011).

Local, regional and national water managers are collaborating to improve the Dutch water system and make it more resilient. For example, work under the Dutch Delta Programme theme 'freshwater supply' explores strategies to sustain the current level of water availability for farmers (MIE & MEA, 2014). Farmers are cooperating with regional water managers and policy makers to improve the 'sponge capacity' of regional water systems (ZON & DHZ, 2015). The programme has identified local storage as part of the solution, but, so far, provided no clear insight into the potential of local storage to offer a secure supply during periods of temporary water shortage. Despite this lack of knowledge, national and regional water managers are negotiating over more decentralized water distribution plans and strategies to reduce water demand from the central water supply system.

To better understand the implications of local water storage strategies, the FWOO method was developed and applied to an area in the province of North Holland. Here, the Hoogheemraadschap Hollands Noorderkwartier water board manages freshwater supply from Lake Ijssel and Lake Marker. The regional Delta Programme has formulated a management strategy specifically for this area (MIE & MEA, 2014). The case-study area consists of two distinct, predominantly agricultural regions: Wieringen and Wieringermeer (Figure 1). Wieringen is a former island, connected to the mainland since the 1924 reclamation of the Wieringermeer polder. Wieringen contains upward and downward seepage areas and has heterogeneously structured subsoil. The Wieringermeer polder is highly productive, with large areas devoted to agriculture, horticulture and greenhouses. The topsoil here is clayey, and the subsoil consists of sand and clay layers.

The case-study area has a long history of water-related stress. In summer, the salt content in ditches increases due to upward seepage of brackish groundwater. This water quality problem becomes more severe when water intake from Lake Ijssel is no longer possible or allowed, for example, during drought. The dry year of 2003 caused significant drought-related yield losses (van Bakel et al., 2008). While in theory water could be supplied to the region by Lake Ijssel and Lake Marker (MIE & MEA, 2014), water of adequate quantity and quality is not always available at the right place and at the right time.

The FWOO outcomes in the case-study area

The FWOO assessment concluded that 16 MCM could be stored in Wieringen and Wieringermeer using the seven local water storage techniques (Nikkels et al., 2015). To put this into perspective, 16 MCM is equivalent to 72 mm, or 32% of the summer rainfall deficit in a typical dry year – i.e., one with a recurrence interval of every 10 years and a precipitation deficit of 220 mm (MIE & MEA, 2011). This is an appreciable quantity – more than the annual volume supplied from Lake Ijssel, which is 11 MCM. The cost per cubic metre stored was found to vary, from €0.07 for aquifer storage and recovery (coastal) to €1.04 for water conservation with small weirs (Nikkels et al., 2015). Discount rates, time horizons and assumed life spans influenced the cost-effectiveness rankings.

Figure 1. Case study area (dark grey in inset).

Challenges in assessing the regional feasibility of local water storage

Based on our literature review and critical reflection on the FWOO case study, we identified eight challenges, grouped into three categories (Table 3). The categories are local context, water system context and farmers' investment decisions.

Local storage techniques and the local context

The first challenge identified in the local context is that exploitable volumes may differ due to differences in manageability and rechargeability. The FWOO method compares storage techniques based on their storage potential at the beginning of the growing season, assigning the same monetary value to each cubic metre of water stored. As such, the method bypasses the distinct characteristics of the different storage options, and manageability remains unaccounted for. This introduces uncertainty to the method's comparisons (Lasage & Verburg, 2015).

Table 3. Eight challenges in assessing the regional feasibility of local water storage techniques based on the literature and fresh water options optimizer (FWOO) application.

Challenges	Based on the literature in Table 1	Based on FWOO application
Local context		
Exploitable volumes differ due to differences in manageability and rechargeability.	McCartney et al., 2013; Van Meter et al., 2016	✓
Stored water serves additional purposes, such as preventing saltwater intrusion into the plant root zone.		✓
Storages impact their direct surroundings, influencing the local feasibility of other techniques.	McCartney et al., 2013; Thomas et al., 2011	✓
Water system context		
The spatial and temporal scales of analysis influence assessment findings regarding the overall feasibility of local storage.	Devineni et al., 2013; Habets et al., 2018; Lasage et al., 2013; Lasage & Verburg, 2015; Van Meter et al., 2016; van Oel et al., 2018	✓
Uncertainty about the local availability of water to fill local storage installations reduces reliability.	McCartney et al., 2013	✓
The actual contribution of local storage to regional objectives is influenced by incorporating alternative sources such as return flows, reuse and regional storage.		✓
Farmers' investment decisions		
Costs and benefits of local storage are hard to quantify, especially when benefits pertain to various spatial and temporal scales.	Lasage & Verburg, 2015; Pandey et al., 2011	✓
Farmers' investment decisions are difficult to predict and may depart from the economically optimal option.	Lasage et al., 2013; Wutich et al., 2014	

For instance, there is a difference between 'water-in-the-hand' techniques, such as Freshmaker and ASR Coastal, and 'water-in-the-land' techniques (the other five techniques considered; see Table 1). Water-in-the-hand techniques store water in waterbodies, from which farmers can extract it when needed. Water-in-the-land techniques store water in the ground at or near the root zone, where it is readily available to plants. The manageability of water stored in the hand is therefore greater. Moreover, water in the land is already in use while farmers can still extract from other sources, such as nearby surface waters. As a result, it may not be available when it is really needed. The actual usefulness of in-the-land techniques is therefore different from the storage potential.

Furthermore, all local storage techniques included in the FWOO assessment may be filled or recharged multiple times during a summer period. This, too, adds uncertainty to the determination and comparison of their cumulative storage capacities. In a rain event – or in the case of Wieringen and Wieringermeer, when withdrawals can again be made from Lake Ijssel – local storage can be refilled. The recharging capacity differs across techniques and depends in part on seasonal conditions and location, which complicates comparisons even more (Lasage, Aerts, Verburg, & Sileshi, 2013). These complicating factors suggest that we need to shift our focus from storage potential to storage feasibility, as improving exploitable water availability involves more than just increasing quantity at the beginning of the growing season.

A second challenge in assessments of local storage relates to the multiple purposes for which water can be stored (Turner, Georgiou, Clark, Brouwe, & Burke, 2004). For instance, stored water can prevent saltwater intrusion in the plant root zone. A stored volume of freshwater can have a dual purpose if a relatively small additional amount of freshwater (e.g., provided by the Drains2Buffer or Freshmaker technique) can prevent saline seepage into the root zone (Zuurbier, Raat, Paalman, Oosterhof, & Stuyfzand, 2016). Such buffering or shielding capacity confers an added value to some stored water units, compared to water that can be used for irrigation purposes only. However, the FWOO method cannot account for this multipurpose characteristic.

Third, the use of certain water storage techniques can have considerable physical or regulatory flow-on consequences, extending to adjacent areas. For instance, water stored using an ASR Coastal system requires implementation of a 'no go' zone for other wells (MIE & MEA, 2015). Techniques that raise water levels in ditches (e.g., water conservation with small weirs) can result in additional water stored in the drainage systems of adjacent fields. While such flow-on impacts are identified in steps 3 and 4 of the FWOO method, their interdependencies are not quantified. Nonetheless, interdependencies can be important, as the best option for water storage might depend on the storage activities of neighbours. It might even be possible to join efforts and cooperate with neighbours and other stakeholders or to implement two techniques at the same location. Therefore, the specificity of the storage location and adjacent storage activities should also be taken into account in local storage technique assessments.

Local storage techniques and the water system context

The feasibility of local water storage techniques and their impacts at the water-system level strongly depend on the broader characteristics of the water system. Hence, the feasibility of local storage options is context-specific. This notion leads to our next three challenges.

The fourth challenge is that any intervention in a water system affects temporal and spatial water availability elsewhere. While local storage might increase the exploitability of water at one location, it could also reduce the exploitability of water downstream (van Oel, Martins, Costa, Wanders, & van Lanen, 2018). This applies to any storage technique, to a change in the water table, and to irrigation practices (Masih, Maskey, Uhlenbrook, & Smakhtin, 2011; van Halsema & Vincent, 2012). Whether a reallocation of water is desirable from a regional perspective depends on the regional water management objectives. The FWOO method focuses on storing water for private use, without fully quantifying system-level effects. This means that regional effects go largely unevaluated, given the impacts of local storage on water availability at different locations and times, through effects on peak flows, base flows and overall water resource distribution (Di Baldassarre et al., 2018; Krol, de Vries, van Oel, & de Araújo, 2011; WCD, 2000). These scale interactions were acknowledged by Habets, Molénat, Carluer, Douez, and Leenhardt (2018), Lasage and Verburg (2015) and Van Meter, Steiff, McLaughlin, and Basu (2016). Nonetheless, they remain poorly understood, hampering local storage technique assessments.

The Dutch national water system, for instance, supplies multiple water management regions. In the case-study area, reduced demand for water from the central source (Lake Ijssel and Lake Marker) could benefit other areas that get their water from the same source. A better understanding of these interdependencies at the system level could yield better infrastructure investment decisions. This could ultimately improve the efficiency and effectiveness of regional water systems by strategically positioning local water storages.

Fifth, there is often uncertainty regarding whether enough water will be available locally to fill small-scale storage structures. This complicates our assessments of the feasibility of using a local storage strategy to increase water availability. The FWOO method assumes that water will be available in the wet winter months to fill storages with high-quality freshwater. Indeed, Lake Ijssel receives much more water than it can store, and the excess is discharged into the Wadden Sea. Although the assumption of abundant winter inflows might be valid at the case-study location, it may not hold true elsewhere in the Netherlands and around the world.

Sixth, varying preferences and needs among competing water users – particularly agriculture, nature, industry and urban areas – might offer opportunities for water storage and reuse. Yet, return flows are currently unaccounted for in the FWOO method. Water is thought of in linear flows and singular high-quality provision. However, temporal and qualitative variety in the demands of different water users might yield storage and reuse opportunities. In the Netherlands, local storage tends to be used for supplementary water; it serves as an alternative source when other sources (usually surface water) become scarce or run dry. Therefore, at least in the Netherlands, we should not limit ourselves to comparisons between central large-scale storage and decentralized local storage techniques, as in van der Zaag and Gupta (2008). Instead, we should try to understand where, how and what local storage techniques could be applied to supplement water availability from central large-scale sources (Figure 2).

According to Blanc (2014), when large and small-scale storage complement each other, the combination of the two can improve water availability for irrigation. A better system-level understanding allows investments in various forms of water storage at strategic locations, resulting in improved robustness of the regional water system.

In the case-study area, local storage techniques could bridge relatively short drought peaks, delivering freshwater to the capillaries of the system. A regional freshwater shortage analysis, as in step 1 of the FWOO method, should therefore start with an investigation of how local storage might 'improve' rather than 'increase' water availability at the appropriate level. The focus here would thus no longer be on storage potential, but on the feasibility of using a local storage strategy to augment water supply in a specific location and context.

Local storage techniques and farmers' investment decisions

The costs of investments in water storage depend on many factors. The cost-effectiveness calculation for the FWOO storage techniques presented in Table 1 represents an attempt to compare and rank options based on the cost of storing one cubic metre of water (Nikkels et al., 2015). The aim was to know what volume of water can be stored and the associated costs, to explore to the optimal set of storages. However, there are large uncertainties in storage capacity, life spans and costs of various components. These will influence the ranking of the techniques. For informed decision making, a much more detailed understanding of the local context, the factors that influence comparison (ranking) of storage options and their (financial) feasibility is needed. This leads to our final two feasibility assessment challenges, which go beyond hydrology and are categorized under farmers' investment decisions.

The seventh challenge is that the costs and benefits of local storage, and water in general, are diverse and hard to quantify (Pandey, Soupir, Singh, Panda, & Pandey, 2011; Savenije & Van der Zaag, 2002; WOCAT, 2007). Water can have cultural, environmental, religious and social benefits, of which the perception is personal (Davidson, Hellegers, & Samad, 2009; Garrick et al., 2017). Also, the costs and benefits of extra water to irrigate crops may differ by year and season, due to variations in commodity prices, usage, rainfall and quality, to name just a few (Turner et al., 2004). Determining the benefits, both monetary and non-monetary, and comparing and ranking options becomes even more challenging if the stored water

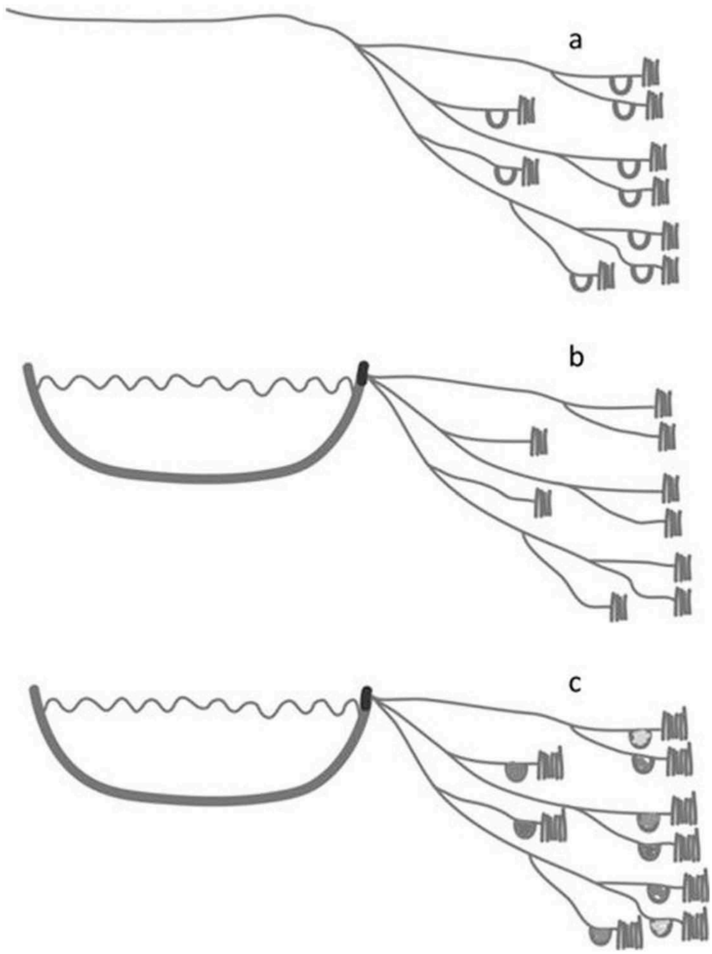

Figure 2. We need to shift from comparing decentralized storage (a) and central storage (b) to assessing where and how local storage techniques can support water supply from a large-scale storage system (c).

serves multiple purposes. Beyond offering local benefits, the water system may receive benefits from local private investments in local storage, which may give governments an opportunity to reduce or postpone their own investments in infrastructure, such as a centralized large-scale reservoir or flood mitigation measures. The benefits they yield at the system level are hard to quantify and can be far removed in both location and time. This makes fair allocation of the investment costs another challenge, especially when the benefits of local storage are not enjoyed at the location where the implementation costs are incurred.

The eighth and final challenge relates to farmers' decisions to invest in local water storage, which is outside the scope of the FWOO. From a policy perspective, it is important to understand how farmers conceptualize the situation and the potential solutions (Wutich et al., 2014) and under which conditions actors make investment decisions (Nikkels et al., 2019). Economic models often rely on a rational economic actor, who seeks to maximize a goal function under conditions of perfect information and in the absence of biases or unequal power relations. Empirical evidence shows, however, that real economic choices often deviate from this model, especially if made under uncertainty (van Duinen, Filatova, Geurts, & van der Veen, 2015; Veraart, van Duinen, & Vreke, 2017). Choices are made based on value-for-money and functional factors, but also for emotional and social reasons (Vanclay, 2004). Van Duinen, Filatova, Jager, and van der Veen (2016) found farmers' uncertainty thresholds, aspiration levels, social network characteristics, heuristics and expectations all to be important factors of drought adaptation behaviour. Preferences among techniques might therefore be personal, in which case a structured assessment method, like FWOO, might best be used as a discussion support tool rather than for decision making (Guillaume, Arshad, Jakeman, Jalava, & Kummu, 2016; Nelson, Holzworth, Hammer, & Hayman, 2002). As farmers might have personal preferences and make different investment decisions than their peers, the focus of the discussion should no longer be on 'what is right' and 'what can be counted' but instead 'what counts', assumptions and personal reasoning (Nikkels, Guillaume, Leith, & Hellegers, 2019).

Discussion and policy implications

The feasibility of local water storage techniques and their impacts at the water-system level strongly depend on the characteristics of the regional water system. In our case, some of the characteristics are not representative of other cases in the Netherlands, nor the world. The ability to recharge local storages during the season, for example, differs across techniques and locations within the case-study area, but is not possible in many other cases. And serving multiple purposes, e.g., preventing saltwater intrusion in the plant root zone, is also context-dependent. Saltwater intrusion is increasingly a problem in Wieringen and Wieringermeer (Oude Essink, 2001), as it is in many other deltas (de Louw, Oude Essink, Stuyfzand, & van der Zee, 2010). However, the multiple-purpose function might be more related to the water system in other contexts. For example, in more mountainous regions, the ability to influence peak flows and to strategically release water to improve flow might be multiple purposes that should be taken into account when comparing options, as did Thomas, Steidl, Dietrich, and Lischeid (2011). Other purposes that go beyond storage capacity, such as the ability to provide ecosystem services, might also be factors worth considering when comparing storage techniques (Mul & Gao, 2016).

From a water-systems perspective, the roles of storage are relevant to consider. Unknowns in climate trajectories and in the demand for water might call for different roles of local storages in the future. Moreover, the variability of water availability between and within years complicates the assessment of local storages (Devineni, Perveen, & Lall, 2013; Habets et al., 2018). These variations and unknowns add to the complexity of assessing their long-term feasibility (Lasage et al., 2013; McCartney, Rebelo, Xenarios, & Smakhtin, 2013). In the Netherlands, local storage is currently a supplementary water source; it serves as an alternative when other sources run dry. In most parts of the Netherlands (under normal conditions), this would be surface water, but during droughts, farmers might use piped municipal water for irrigation, or arrange for trucks to haul in water, though this incurs additional production costs. Elsewhere in the world, local storage may constitute the principal – or even the only – means of increasing the amount of water available in the growing season (Hughes & Mantel, 2010; van Oel, Krol, & Hoekstra, 2011).

In other contexts, interaction between surface and groundwater (Devineni et al., 2013) and the codependencies between built and natural water storages might influence the feasibility of newly built storages. Mul et al. (2015) mentioned that natural storages can have positive effects on water quality, which then relates to the maintenance requirements of built storages. Saruchera and Lautze (2019) found that in Africa, sedimentation and poor maintenance are key factors determining performance during the lifespan of storages. They argue that for improving the performance of storages strong institutions are needed, and they raise the issue that NGOs and governments may lack incentives to finance well-structured storages that have a long lifespan. In other contexts, the regional feasibility of local water storage might be more closely linked to institutional and financing challenges.

The challenges related to investment decisions are not specific to the water sector. They also pertain to the energy sector, for example. Optimal deployment of centralized and decentralized energy resources at the system level is a key challenge in multi-energy systems and features prominently in concepts such as the 'smart grid' (Mancarella, 2014). Mancarella (2014) pointed to the general lack of understanding of the economic feasibility of future 'smart' multi-energy systems under current and future uncertainties. A comparison of the consumer energy cost for a mix of centralized and decentralized heat and power techniques revealed that optimal solutions may be found in combinations of both (Aki, Oyama, & Tsuji, 2006).

Developing policies that align private and public initiatives and support innovation often requires changing existing institutional arrangements and their governance (Godfrey-Wood, 2016). New policy options might emerge from social learning approaches in which actors learn from and with others, called 'learning together to manage together' by Ridder, Mostert, Wolters, and HarmoniCOP Team (2005). A policy implication is that such social learning processes could provide valuable information and insights on the factors that influence personal preferences and could enrich the knowledge of potential investors so they can make better-informed investment decisions. This is beneficial for the cooperation between farmers and water managers and would contribute to reaching both on-farm and water-system objectives.

These complicating factors strengthen our recommendation to shift from focussing on storage potential to storage feasibility. Feasibility determination is very context-specific; the roles that local storages (can) play to improve regional water availability depend on the unique characteristics of the water system, but also on the objectives of (long-term) water management, institutions and policy plans.

We hope that the identified and discussed challenges raise awareness and function as warnings for anyone undertaking an analysis of local storage techniques. As such, this article concurs with van der Zaag and Gupta (2008), who called for research into the cumulative effects of local water storage techniques. This first step provides guidance for further research in assessing the regional feasibility of local water storage in various settings and from different (inter)disciplinary perspectives.

Concluding remarks

The objective of this article was to identify and discuss challenges in assessing the regional feasibility of local water storage techniques. We presented eight such challenges (Table 2). We find that the cumulative effect of multiple local storage techniques in a water system is not a simple aggregation of individual outcomes. Indeed, the aggregate potential of local water storage, measured by the quantity of water that could be stored and the corresponding costs, might differ from the amount of storage that such systems can feasibly be expected to provide on a regional scale. Thus, we argue that the focus needs to shift from storage 'potential' to 'feasibility'.

Local water storage techniques may have the potential to improve regional water availability, but our understanding of the feasibility of using combinations of different local techniques remains vague, due to the eight challenges we have identified. These challenges were grouped into three categories: local context, water system context and farmers' investment decisions. First, the local context needs to be analyzed and understood before it can be included in any meaningful analysis. Feasibility depends on the exploitability, purpose and interactions of the various water storage alternatives. Second, the spatial and temporal scales of analysis have considerable influence on feasibility. Finally, investments in local storage will hinge on the benefits of the stored water and on the investment preferences of farmers, who are influenced by difficult-to-quantify factors, such as risk aversion and personal values.

We conclude that in order to make the best possible policy and investment decisions for local water storage, concerted effort is needed regarding each of the identified challenges, to improve storage assessment tools and processes.

Note

1. Papers that do not directly relate to the call for research on the regional effects of local water storage are summarized in the Appendix.

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ORCID

M. J. Nikkels http://orcid.org/0000-0002-7240-9580
P. R. van Oel http://orcid.org/0000-0001-7740-0537
H. Meinke http://orcid.org/0000-0003-2657-3264
P. J. G. J. Hellegers http://orcid.org/0000-0002-4134-0568

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Appendix

Table A1. Conclusions and recommendations for further research in articles that refer to van der Zaag and Gupta (2008) but do not directly relate to their call for research on the regional effects of local water storage.

Ghimire and Johnston (2019) present an assessment to score the sustainability of agricultural systems. The sustainability score includes rainwater harvesting techniques and well-water systems. There is no mention of the challenges in assessing the cumulative effects of these systems.
Rufin et al. (2018) compare cropping frequencies of irrigation dam command areas. As this is a global assessment, their understanding of a small dam is everything less than 7.9 MCM. They recommend that future research focus on water losses and local access to irrigation water.
Ouma (2016) compares two techniques to find the most suitable location for a large dam in Uasin Gishu County in Kenya. He esitmates site feasibility, including storage potential, but does not consider system interactions.
Duvail et al. (2014) make use of a participatory monitoring system to collect water levels in nine lakes, along with rainfall and food data. They also use a simple water balance model to explore the influence of a large dam planned for Stiegler's Gorge in Tanzania and find that the lake levels are sensitive to changes in flow and precipitation. The authors argue that their approach may help local users understand the hydrological system and adjust to changes but highlight that judicial imperfections and power imbalances hamper the influence of local users in their case study.
Norman, Dunn, Bakker, Allen, and de Albuquerque (2013) develop the Water Security Status Indicators method for assessing water security and apply the model in a case study area in British Columbia (Canada). Their assessment does not include water storage.
Pandey, van der Zaag, Soupir, and Singh (2013) show that on-farm storage increases the benefits of rainfed agriculture in a case-study area in the Indo-Gangetic Plain of India. Harvesting rainwater provides supplemental irrigation and increases downstream groundwater availability in their case study. The authors focus on crop yields and find large differences in the benefits of local storages between wet and dry seasons. The authors assess a single storage and do not discuss further implications of a set of storages.
Masih et al. (2011) calculate the downstream effects of increasing water consumption in the Karkheh Basin, Iran. They find that converting rainfed areas to irrigated agriculture reduces flows downstream. The authors focus on the downstream impacts of irrigation and recommend further exploring the impact of storage in future research. Their paper is a chapter in Masih's PhD thesis (Masih, 2011).
Love, van der Zaag, Uhlenbrook, and Owen (2011) use a water balance model to determine the potential for expanding irrigation and to explore water allocation options in the Limpopo basin, Zimbabwe. Their model includes both surface and groundwater resources to explore conjunctive use of surface reservoirs and alluvial aquifers. They find that irrigation can be expanded with the existing dams when making better use of groundwater. The authors recommend that future studies investigate water supply from alluvial aquifers when considering building a new dam.
Merrey (2009) argues that transnational river basin management institutions will acquire more legitimacy and effectiveness if they build on African institutional processes, i.e., stronger focus on local knowledge and stakeholder participation. The focus of this paper is institutional and transnational, with no links to local storage.