DeltaMAR
Project Output Report

September, 2020

Authors

Frank van Laerhoven (project coordinator)

Kazi Matin Uddin Ahmed (project coordinator – Bangladesh)

Boris van Breukelen, Paul Schot, Jasper Griffioen, Shantanu Majumder, Imran Hasan, Risalat Rafiq, Badrul Hasan, Floris Naus, Koos Groen

Participating institutions

Universiteit Utrecht TUDelft UNIVERSTY OF DHAKA ESTABLISHED: 1921 ACACIAWATER

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NWO unicef UNIVERSTY OF DHAKA ESTABLISHED: 1921 ACACIAWATER

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Executive summary

The aim of the DeltaMAR project is to enhance fundamental knowledge on factors that influence the potential of underground freshwater buffers in saline deltas through Managed Aquifer Recharge (MAR). The research focuses on optimization of design, operation, governance and siting of small-scale systems in rural communities and peri-urban areas in Southwestern Bangladesh.

This report presents the results of the DeltaMAR project in the form of Guidelines related to:

- MAR Water Quality
- MAR Governance
- Regional MAR site selection

The target audience of these guidelines consist of national and regional policy makers and water supply professionals, donor organizations, NGO's, local communities and entrepreneurs that have an interest in fresh (drinking) water supply, particularly in southwest Bangladesh.

The DeltaMAR project is executed by a consortium of partner institutions that include Utrecht University, Delft University of Technology, University of Dhaka, and Acacia Water

The project was funded by a grant of the Dutch Research Council (NWO) under the Urbanizing Deltas of the World (UDW) research program. Detailed information about DeltaMAR can be found on the project website and on the website of the project funder.

1. Drinking water problems and MAR as a solution

DRINKING WATER PROBLEMS IN SOUTHWESTERN BANGLADESH

Coastal regions and deltas are among the most heavily populated areas in the world and their water resources are experiencing increasing stress. One of the largest and most densely populated deltas is the Ganges–Brahmaputra–Meghna (GBM) delta. Here, manifestations of this stress are arsenic contamination of shallow groundwater resources, severe pollution of surface water resources, and limited availability of the meteorological water resources, due to pronounced seasonality. In the coastal southwestern region of Bangladesh, available drinking water is further limited by the salinity of surface- and groundwater. The groundwater salinity variation in the coastal area is large and, therefore, local occurrence is hard to predict. The stress of saline water intrusion on the groundwater is increasing due to natural changes in the form of natural land subsidence and sea level rise, and due to anthropogenic changes in the form of man-induced land subsidence, decreased Ganges outflow and increased groundwater extraction.

MAR AND ITS ADVANTAGES

In a MAR system, water is collected from ponds and rooftop rainwater. After passing through a sand filter, the water is infiltrated into the aquifer to create a bubble of fresh water. Users can subsequently abstract the water using standard hand tube-well pumps (see figure 1).

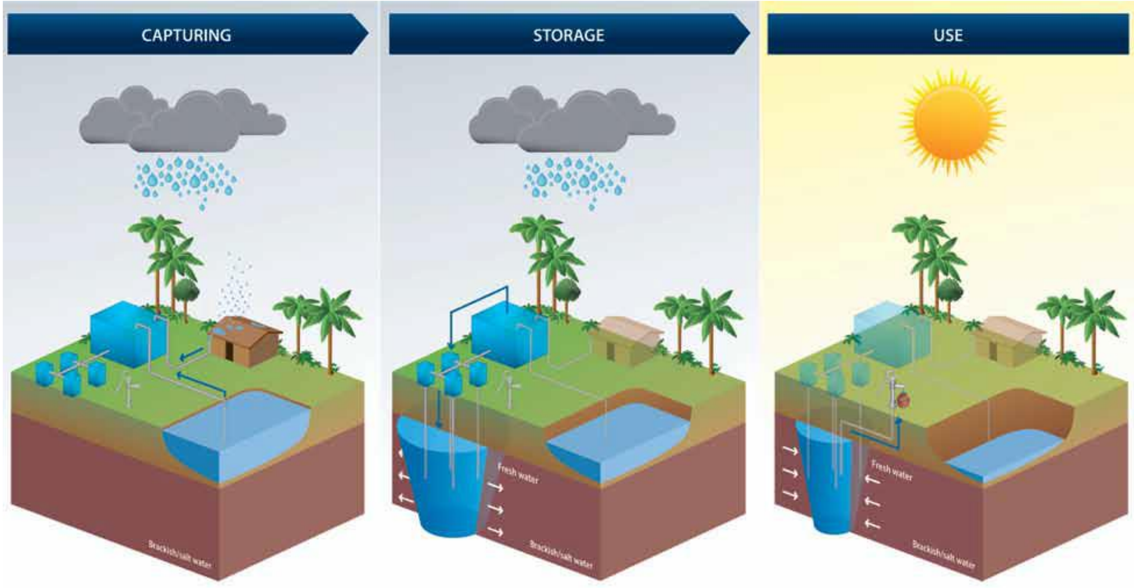

FIGURE 1: SCHEMATIC REPRESENTATION OF MANAGED AQUIFER RECHARGE (MAR) TECHNOLOGY FOR THE COASTAL REGIONS OF BANGLADESH (SOURCE: TOLK ET AL. 2014)

Figure 2 shows an example of a layout of the infiltration and abstraction (i.e. drinking) wells that make up the MAR system.

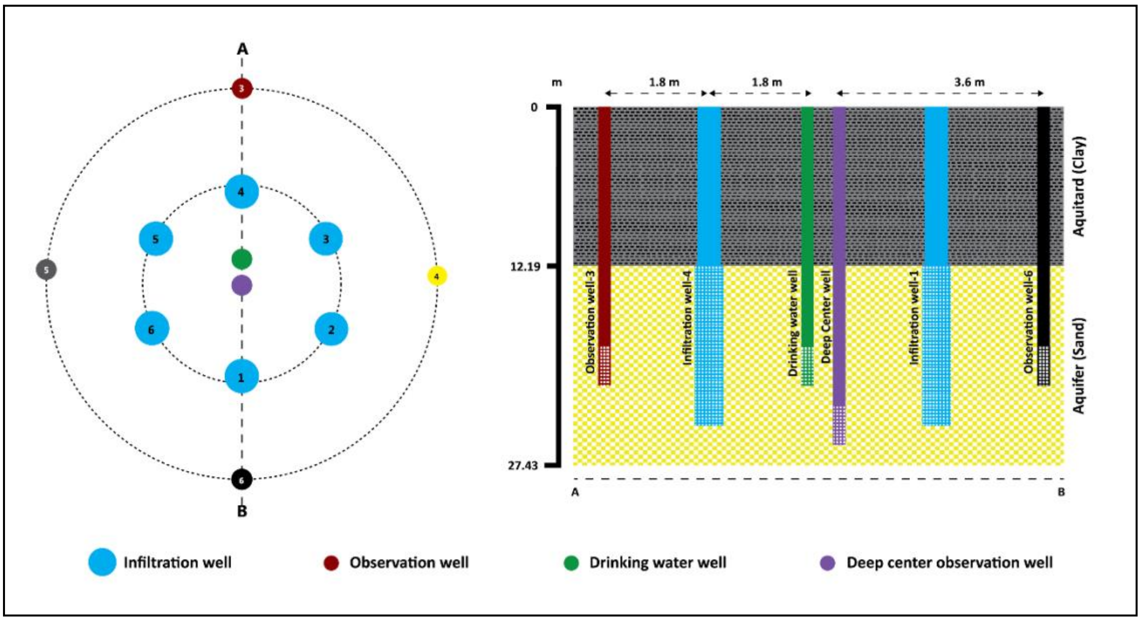

FIGURE 2: SCHEMATIC LAYOUT OF SITE GMF11 SITE IN MAP VIEW (LEFT) AND IN CROSS-SECTIONAL VIEW (RIGHT).

Compared to other major drinking water systems in the area, MAR is contamination free, cyclone proof, and it is reliable as it provides water in sufficient quantities of drinking water throughout the year. In terms of installation costs, MAR is considerably less expensive than most of the available alternatives.

It is also relatively easy to operate. In sum, MAR advantages include:

- Improved year-round water availability
- Improved water quality and reduced health risks
- Suitable for local-scale application
- Cost-effectiveness
- Resilience to disasters

In order to achieve these relative benefits, it is important to optimize:

- Water quality
- MAR governance, and
- Site selection

These goals are interrelated, and the guidelines presented in this report should be taken as an integrated whole (figure 3)

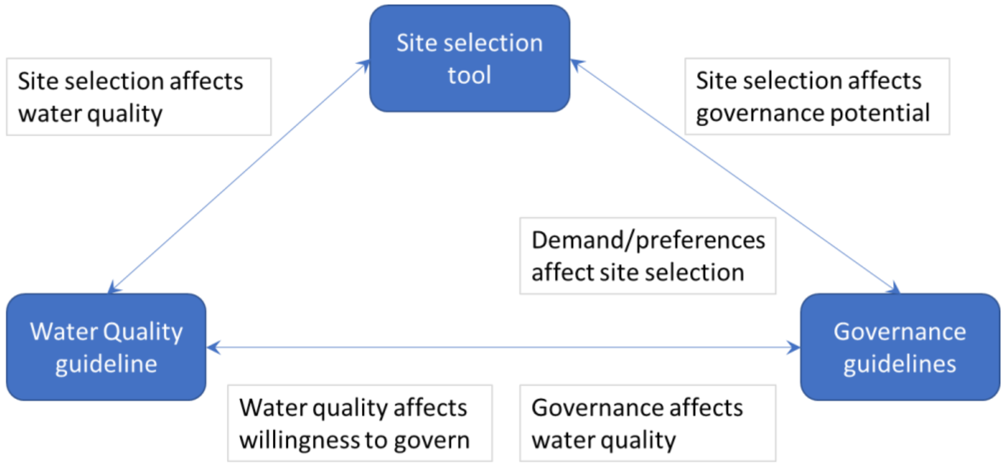

FIGURE 3: THE INTERRELATION BETWEEN THE OPTIMIZATION OF WATER QUALITY, GOVERNANCE, AND SITE SELECTION.

2. The introduction and promotion of MAR in Bangladesh

UNICEF MAR PILOT PROJECT

In southwestern Bangladesh, MAR has been piloted as a suitable sustainable drinking water option in parts of the region where none of the other safe alternatives are available in the form of small-scale, community-run systems in a project funded by UNICEF. This project started with a pilot of 20 systems from 2009 to 2013, followed by the construction of another 79 pilot MAR systems in 2013 and 2014. After installation, the MAR systems were donated to the local communities, which were expected to run and maintain the systems themselves.

Both success and failure were observed in the pilot MAR systems. Some MAR systems did not manage to produce water of sufficient quality, indicating unforeseen hydro-chemical and hydraulic processes. Other MAR systems were not well-operated or maintained, indicating problems with the governance structure of the MAR systems. Additionally, much was unknown about whether MAR could be successful throughout the southwestern region in Bangladesh, related to a lack of understanding of the hydrogeological conditions throughout the region.

DELTAMAR PROJECT

The DeltaMAR project was started in 2013 to address the above-mentioned problems and knowledge gaps. It was funded by the Dutch Research Council (NWO) under the

Urbanizing Deltas of the World (UDW) program. It was undertaken by a consortium of Utrecht University, Delft University of Technology, Dhaka University and Acacia Water.

The DeltaMAR research was set-up around four PhD research projects to elucidate knowledge gaps regarding

- hydraulic processes during MAR, and effects of **design and operation** choices;
- effects of hydro-chemical processes on the **water quality** during MAR;
- effects of the **governance** structure on the success of MAR systems;
- the **regional potential of MAR systems** being successful in the hydro-geologically highly variable region of southwestern Bangladesh.

This report presents a summary of the DeltaMAR project results in the form of guidelines to be used by various kinds of stakeholders involved with provision of safe drinking water in southwestern Bangladesh, such as water supply professionals, national and regional policy makers, donor organizations, NGO's, entrepreneurs and local communities.

MAR-CAB PROJECT

The MAR-CAB project is a follow-up to the DeltaMAR project and is aimed at enhancing local capability for mainstreaming MAR in Coastal Areas of Bangladesh. It started in 2020 and will end in 2021. It is funded by the Dutch Research Council (NWO) under the Urbanizing Deltas of the World (UDW) program. It is undertaken by a consortium of Dhaka University, Acacia Water and Utrecht University.

The DeltaMAR research project resulted in defining parameters for MAR in coastal Bangladesh, with regard to both physical/geohydrological and governance aspects This report). Using the parameters, it is possible to define zones in the coastal belt where MAR is feasible. However, for direct implementation under the Bangladesh Delta Plan 2100, practical designs for on-the-ground-implementation are still missing. Also, there is need for training personnel at local levels for designing, implementing and operating MAR systems independently without support from organizations like Dhaka University and Acacia Water. The MAR-CAB project aims at:

- Creation of practical technical and policy guidelines and continuation of capacity development on the application of MAR systems in coastal Bangladesh;
- Creating awareness for the possible scopes of MAR application beyond the existing small-scale drinking water MAR systems;

- Contributing to professionalizing contractors and the well-drilling sector;
- Enhancing capacity of local level officials

The ultimate outcome of the project is to contribute to the national guidelines for MAR implementation to be adopted by the high-level national committee on MAR (HLNC) and the technical committee of MAR (TC) of Bangladesh Government.

3. Water Quality Guidelines

DEFINING MAR IN BANGLADESH

This chapter provides general guidelines and recommendations with the aim to improve the water quality of the current and potential future MAR systems in coastal SW Bangladesh[1].

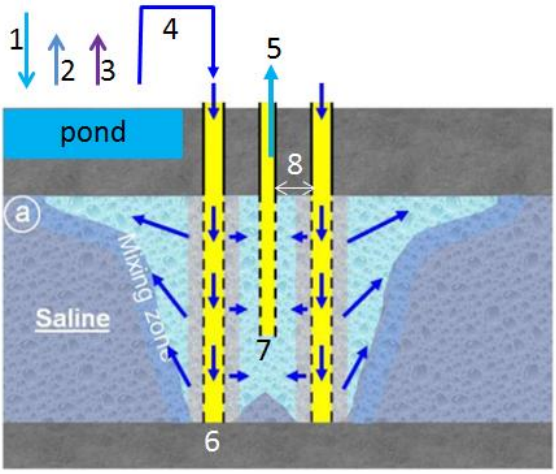

FIGURE 4: DIAGRAM OF MAR SYSTEMS AS IMPLEMENTED IN SOUTHWESTERN BANGLADESH

A primary design criteria for MAR is the available amount of water for infiltration. In figure 4 some important characteristics are presented.

- The maximum amount of infiltration water available for MAR (#4) depends on the yearly amount of rainfall (#1) minus the yearly amount of open water evaporation (#2), multiplied with the surface area of the pond used to feed the MAR.
- Other water uses of the pond like water fetching (#3) needs to be subtracted.
- Another design parameter is the amount of water abstracted by the MAR system (#5).
- Infiltration (#4) should (largely) exceed abstraction (#5) at least on yearly basis. This is to prevent salinization of the freshwater bubble (cyan colour in figure 4) by mixing with saline water (purple), which is present in large part of southwestern Bangladesh groundwater.
- Abstraction (#5) also aids in flushing of the core of the bubble and water quality improvements. High abstraction rates together with even higher infiltration rates are therefore expected to lead to best water quality in shortest duration.

[1] The guidelines for water quality improvement are based on the PhD research by Risalat Rafiq and the work of Imran Hasan.

- Given the projected infiltration and abstraction rates, and properties of the aquifer (permeability, salinity, thickness), the optimal lengths (and number) of the infiltration wells (#6) and the optimal length of the abstraction well (#7) placed at the top of the aquifer, as well as their horizontal spacing (#8) can be calculated/estimated.

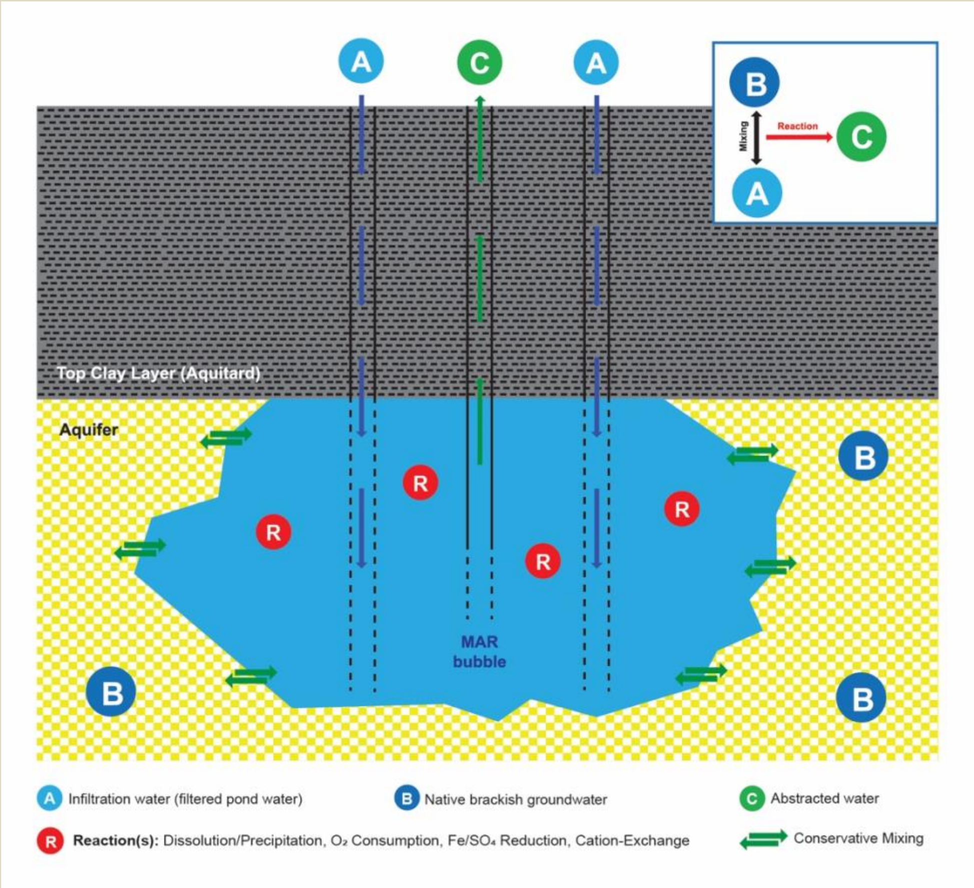

FIGURE 5: A CROSS-SECTIONAL VIEW SHOWING HOW MAR CREATES A FRESHWATER BUBBLE

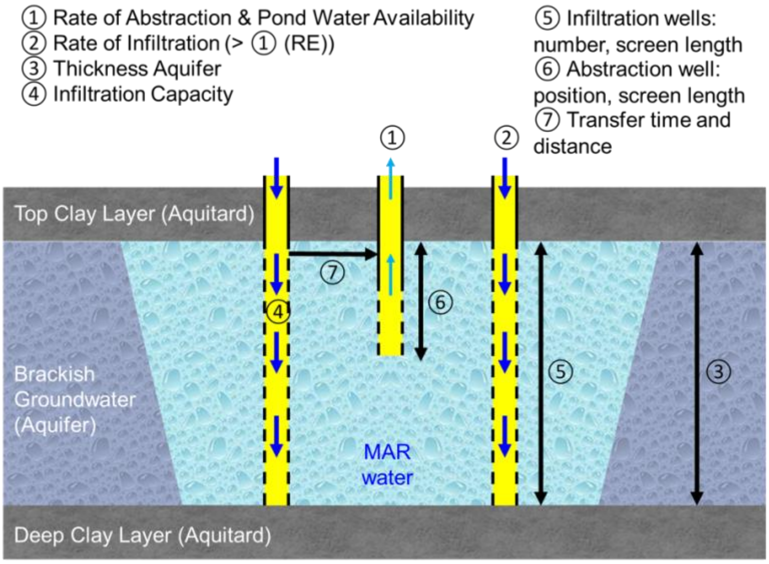

FIGURE 6: CONSIDERATIONS FOR OPTIMIZING WATER QUALITY

PARAMETERS FOR MAR WATER QUALITY IMPROVEMENT

Based on our research, we have identified the following parameters with the potential to improve MAR water quality. The parameters each have implication for intervention strategies aimed at the improvement of water quality. These strategies are closely related with (i) freshwater recovery, (ii) MAR governance, and (iii) site selection, showing the need for an **integrated approach** to MAR (see table 1).

TABLE 1: PARAMETERS WITH THE POTENTIAL TO IMPROVE MAR WATER QUALITY

Parameter	Implications for interventions to improve water quality
Clean pond water	*Site selection:* Ensure that the pond water quality is not compromised by pollution sources like discharge of latrines, dirty water, and litter. Analysis of dissolved organic carbon advised. *MAR governance:* Can the pond be kept clean or cleaned up when used for MAR? The higher the pond water quality, the higher the MAR WQ.
Sufficient supply of pond water	*Site selection:* The more pond water is available for MAR (thus the larger the pond's surface area), the more water can potentially be infiltrated, the larger the stored fresh water bubble becomes, and the less MAR water in the core at the abstraction well may mix with the native groundwater being of poor WQ (brackish; frequently high Fe, Mn, As).
Large(r) rates of infiltration	*Site selection:* See above. The more pond water is available for MAR (thus the larger the pond's surface area), the more water can potentially be infiltrated *Fresh water recovery:* The capacity of the infiltration wells is sufficiently high *MAR governance:* The human capacity is sufficiently high (i.e. the number of hours caretaker(s) can spend each day on letting the MAR system infiltrate).
Avoid locations with high levels of geogenic elements (Fe, As, Mn) in groundwater	*Site selection:* Select locations where the native groundwater is low in the geogenic elements Fe, Mn, and especially As. In case some mixing of infiltration water and native groundwater occurs, the MAR water becomes (much) less deteriorated in water quality. Also select locations where the sediment content is low in organic matter. *Fresh water recovery:* In case background levels are high, high infiltration and abstraction rates are essential.
Adjust the lengths of the infiltration wells to projected rates of infiltration	*Fresh water recovery:* We found that in case the target infiltration rate is too low compared to the (default) lengths of the infiltration wells, relatively small diameter freshwater "bubbles" are formed, which are more vulnerable for mixing with native groundwater by dispersion and buoyancy effects. With shorter infiltration wells, the radius of the bubble will be larger, probably leading to less mixing with native

	groundwater. Information on infiltration capacity (SP1) is essential for meeting this water quality conditions.
Make the abstraction well only at the bottom 1-2 m shorter than the infiltration wells	*Fresh water recovery:* This finding of our research led to proposing an adjustment in the design of the pilot MARs: In contrast to the current design, the abstraction well should not be centred in the middle of the bubble but should have almost equal length as the infiltration wells except at the bottom where it should be 1-2 m shorter to delay the moment of salt water inflow at the bottom.
Increase the rate of "flushing" between infiltration and abstraction wells	Our research (SP2) shows that oxygen in pond water has positive effects on the removal of Fe, Mn, and As. Oxygen is however rapidly consumed in the MAR bubble, while (longer) anaerobic conditions may lead to elevated Fe/Mn/As levels as organic matter from the pond may dissolve iron-oxides sorbing Mn and As. Flushing of the core of the freshwater bubble is enhanced when infiltration and particularly abstraction rates are higher. Water quality in "failed" MAR systems may have remained poor because of limited abstraction (as the water quality was poor). The MAR systems may thus need a start-up time or even a development time where the MAR water is deliberately abstracted at rates (almost) equal to infiltration rates to speed up the oxygenation of the core of the freshwater bubble. To consider: • Inject at start up (chemical) oxidants to oxidize the core of the freshwater bubble? Especially nitrate could be promising. • Consider even subsurface iron-removal (SIR) in the abstraction well as a more effective way to oxygenate the core

DESIGN CRITERIA FOR IMPROVED MAR WATER QUALITY:

A next step is to formulate design criteria that are in line with the conditions for improved MAR water quality listed in table 5, above. These design criteria are to serve as a set of steps that need to be taken when selecting a site and building a MAR, in order to produce good quality water[2].

[2] This step will be further developed in the MAR-CAP project led by Dhaka University, in collaboration with Utrecht University and Acacia Water.

TABLE 2: DESIGN CRITERIA FOR IMPROVED MAR WATER QUALITY

Design criteria	Tasks to be executed
1. Determine water availability for MAR	
Calculate water balance of the pond	Calculate the water balance to determine how much water is max available for MAR.
Determine expected MAR water use and set upper limit on infiltration rate	Estimate the maximum amount of MAR water than can be expected to be abstracted based on population density around ponds and willingness to use MAR. It is essential to have an idea on how much water could be asked for by the local community. When abstraction is lower than what maximally can be infiltrated there is no need to infiltrate more. However, in this case water quality would be less than it could be. Less use or abstraction means less flushing, meaning that it would take longer for good water quality to become available[3].
Establish infiltration capacity	Based on the calculated water balance and the expected MAR use, the infiltration and abstraction capacity can be calculated, as well as the minimum number of wells and their lengths.

[3] See table 1: condition *Increase the rate of "flushing" between infiltration and abstraction wells*

2. Optimize recovery efficiency	
Optimize well lengths	Provide a simple equation and formulate the assumptions to estimate recovery efficiency. Note that although these recovery efficiency values are not directly applicable to the MAR systems in the UNICEF pilot (but apply only for classical MAR systems), we expect them to give an idea of how recovery efficiency could be improved by optimizing the infiltration and abstraction well lengths given a certain pond and native aquifer salinity, aquifer permeability, and infiltration (and abstraction) rate. Eventually we expect to be able to update the above with insights gained from the SEAWAT model (SP1 & SP2). To consider: • Optimize the horizontal spacing of infiltration and abstraction wells. • Simple equations to calculate travel times from infiltration to abstraction depending on abstraction rate.
3. Determine geogenic elements and travel times	
Determine expected mixing of geogenic elements in MAR water	Based on the previous, calculate water quality deterioration by mixing of geogenic elements.
Establish travel time	calculation travel time as an indicative measure of pathogen removal.
4. Analyse bio-geo-chemical processes	
Biogeochemical processes in MAR bubble	Calculate the expected biogeochemical processes in the freshwater bubble and how they improve or deteriorate the water quality in relation to operational/design conditions.

4. Governance Guidelines

This chapter provides general guidelines and recommendations with the aim to improve different aspects related with the governance of MAR systems in coastal Southwester Bangladesh[4].

SUMMARY

The recommendations based on the findings of our research can be summarized as follows:

Selecting communities

- When selecting a site (see site selection guidelines) make sure to establish in detail the community's preferences regarding that different attributes of a drinking water delivery system.
- Assess the number and nature of drinking water solutions that are already available.
- Do not target full and exclusive acceptance of MAR. Households use a portfolio of sources that, in varying ways, to varying extents satisfy one or more out of several preferences they have with regard to their drinking water needs. The size and composition of that portfolio may depend on local supply, time (i.e., season), the specifics of a family drinking water needs (i.e., family size and composition), household characteristics (e.g., income and location), and norms of the wider community that the household is a part of.
- Communities value systems that are cyclone proof, and that provide safe (i.e. high quality), tasty water reliably and in sufficient quantities. Guarantee that the system you are promoting offers all that (see also water quality guidelines).
- When working with poor households, focus on health and reliability features in particular, as these are the attributes that they value in particular.
- In your attempt to have households adapting MAR, raise awareness based on an explicit narrative that stresses its performance with specific regard to these attributes.

Preparing communities

- Although people may not like it, attempts should be made to set boundary rules that determine who can use the system. This is important to guarantee that benefits associated with appropriation (i.e. access to water) are proportional to provision costs (i.e. contributions to the operation and maintenance of the drinking water system).

[4] The guidelines for MAR governance are based on the methods and results described in the PhD Thesis of Badrul Hasan. A link will be added as soon as it becomes available.

- Have communities forming user groups that are large enough to achieve economies of scale – i.e. there should be enough members to pool the money needed for covering (unanticipated spikes in) operation and maintenance costs.
- As working together is something you can learn, encourage households to form groups with members that have collaborated for other types of purposes, before. In awareness raising, use a narrative that includes a focus on the success of other forms of collaboration between the members. Let community members reflect on what worked and what didn't in other forms of collaboration and ask them to use these lessons learned in setting up their MAR user group.
- In order to wean households off pond water, and have them switching to (e.g.) MAR, it is recommended to focus awareness raising campaigns on the risk and inconvenience of drinking pond water. The largest potential for getting shallow tube well users to adopt alternative, safe options is to focus on the risk associated with drinking groundwater with elevated levels of arsenic or salinity.

Supporting communities

- Focus on *hardware* (i.e. make sure that the physical infrastructure works optimally and delivers high-quality water, reliably and in sufficient quantities), but equally important, also focus on so-called *software* activities (i.e. activities regarding the changing people's habits and behaviour).
- Prioritize the support of *collective action* among the users of a MAR system over more conventional forms of support that focus on the transfer of knowledge (such as training, capacity building, and awareness raising) and resources (such as infrastructure and financial contributions).
- Involve the users of the drinking water system in the crafting of all rules regarding its governance – i.e. both with regard to the operational rules (or, day-to-day rules regarding the use and operation of MAR) and the collective choice rules (or, the rules to decide on how day-to-day rules are changed). Focus on community empowerment and allowing users to craft their own ways of meeting the requirements for successful and durable forms of collective action.
- Communities and contexts differ. Therefore, attempts to support communities running a MAR, should experiment with different approaches and activities, and monitor and evaluate the outcomes thereof, in order to learn what works and what does not. Do not provide support agencies (e.g. NGOs or DPHE officials) with a straitjacket made of rigid instructions that are based on predefined problem definitions.
- Invest in a creating trust between users and public agencies, and in transparency with regard to the making and enforcing of rules.

DEFINING THE GOVERNANCE OF MAR

A MAR system can be seen as a *socio-technological system*. In these guidelines, we consider a MAR system as (i) the actual physical infrastructure (i.e., the *resource system*) that produces (ii) drinking water (the *resource units*), plus (iii) the set of end-users that together with others (i.e., the *actors*) engage in the (iv) *governance* of the system (figure 7).

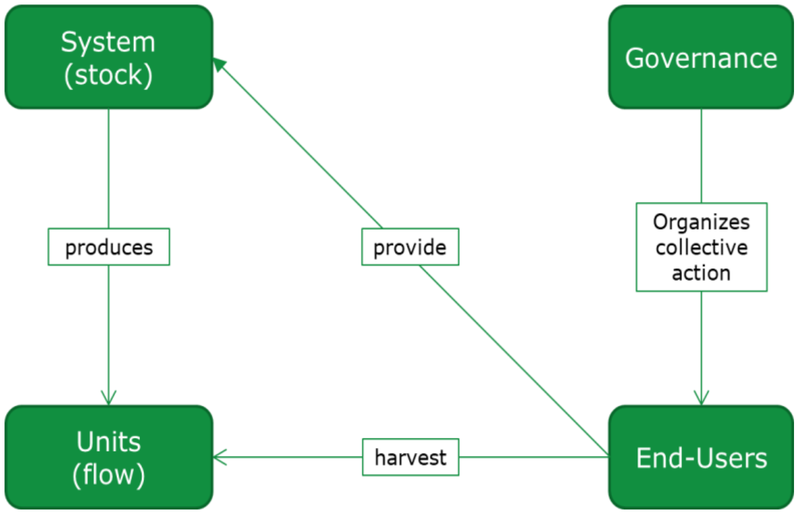

FIGURE 7: DRINKING WATER FROM A SYSTEM ANALYTICAL PERSPECTIVE

Individual users face a *provision dilemma*, as costs related to the investment in the operation and maintenance (i.e. effort or resources) are private costs, whereas the benefits of the joint investment (e.g., a well-working MAR infrastructure) are shared among the group of users of that system. As a result, individual users are tempted to under-invest in operation and maintenance.

Appropriation dilemmas occur because the benefits related to the extraction of water are private benefits, whereas the costs of this extraction (e.g., a decreasing production capacity of MAR) are shared among the whole group of end users. As a result, individual users are tempted to extract too much water, such that the combined extraction exceeds the depletion rate.

By governance we mean the range of political, organizational, and administrative processes through which government and non-government stakeholders articulate their interests, exercise their legal rights, take decisions, meet their obligations, and mediate their differences. Whereas *management* refers to the organization of the operation and maintenance of MAR, *governance* refers to the broader set of actors that can, could or should play a role in determining the parameters for management.

The primary objective of good governance of MAR is:

(i) to counter the tendency of individuals to under-invest in operation and maintenance, and;

(ii) to counter the tendency of individuals to over-exploit the pool of MAR water.

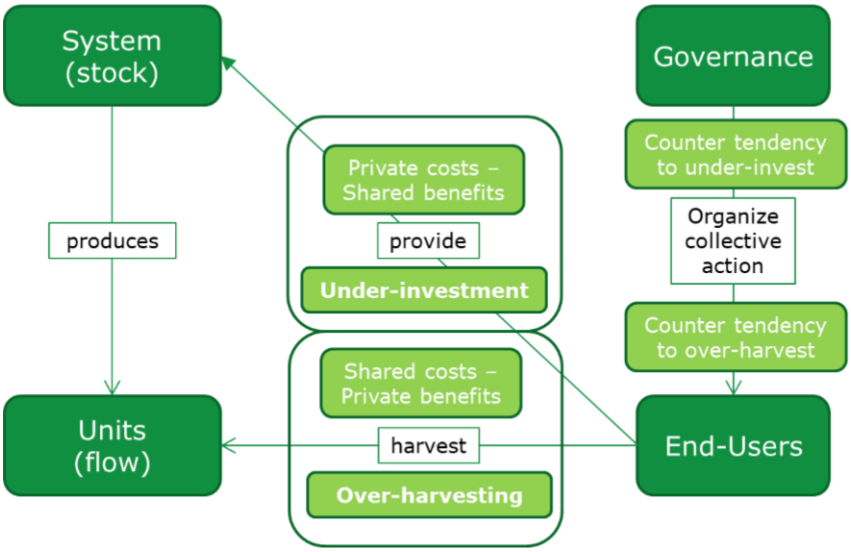

FIGURE 8: A DRINKING WATER TRAGEDY OF THE COMMONS

As is the case with many rural drinking water systems in Bangladesh, the operation and maintenance of MAR is to rely to a large extent on a *community management service model*. Bangladesh's National Policy for Safe Water Supply and Sanitation (1998) explicitly calls for community participation in the governance of drinking water systems.

Hutchings et al. (2015, p.153)) state that "*for too long the assumption that consumers can run their own water supply has led to situations of communities unable to cope with management of their schemes, poor maintenance, lack of financing, breakdowns, poor water quality, lack of support and, ultimately, an unreliable and disrupted supply of water to households*." Harvey and Reed (2007, p365)) hold that *"[i]f community management systems are to be sustainable, they require ongoing support*." In other words, pure self-governance models depending on sustainable, ongoing collective action among the end-users of MAR may well be a dead-end road. Support is needed. Who can give this support? What should the support consist of?

We propose a set of guidelines for what we call Community Management Plus^{+} - i.e. a form of community management embedded in an appropriate support structure with roles for NGOs, DPHE and authorities. In what follows, we will address the following questions:

- What are the requirements for community management?
- How can NGOs support communities?
- How can DPHE assist communities?

WHAT ARE THE REQUIREMENTS FOR COMMUNITY MANAGEMENT?

From our research we have learned that the following appears to increase the likelihood of success of community management service models for a drinking water system like MAR. We differentiate between requirements for day-to-day and for durable collective action, respectively.

TABLE 3: COMMUNITY REQUIREMENTS FOR COLLECTIVE ACTION

Day-to-day collective action
MAR users have an arrangement of regular meetings in place to discuss the issues related to the operation and maintenance of the MAR system
There is a clear arrangement regarding who has access to the MAR site
There are rules in place regarding who can extract how much water, and when
There is a mechanism in place to monitor MAR use and rule compliance
There is a mechanism in place to punish rule breakers
There is a mechanism in place to hold monitor/s accountable to the MAR users.
There is a low-cost system in place to resolve conflict between users
Durable collective action
All resource users understand the rules and policies guiding the management MAR
General users – not only committee members – have the opportunity to participate at all levels of the decision-making process regarding MAR governance
MAR users have the technical and managerial skill and knowledge required to manage and operate the system
There is a system in place to fairly allocate the benefits (e.g. water) and burdens (e.g. costs) associated with the resource among the users
The users have sufficient financial means to pay for the operation and maintenance of the MAR system
The users are willing to pay for the operation and maintenance of the MAR system
All the users are aware of MAR, its operation and maintenance rules and the activities of the committee that is responsible for the management
Leadership is closely familiar with the changing external governance environment, has frequent interactions with all users and regular contact with local traditional leaders
The autonomy of users to manage their MAR system is not significantly undermined by any external authority

HOW CAN NGOS SUPPORT COMMUNITIES?

Evidence from our research suggests that the users of a drinking water system like MAR often face collective action dilemmas that are difficult for them to overcome, independently. In too many cases still, this leads to the abandonment of drinking water systems. We see that NGOs often step in or are called upon to support the development and consolidation of collective action (or, organization) among the group of users of a drinking water system. How can NGOs best support community management? How can they best help communities to meet the criteria listed in the section, above?

In the table 4 below, we list activities that NGOs have reported to us to engage in with MAR users to (implicitly or explicitly) address the design principles for successful community management of MAR.

TABLE 4: NGO ACTIVITIES TARGETING COMMUNITY REQUIREMENTS FOR COLLECTIVE ACTION

Community requirements for collective action	**Reported NGO activities targeting community requirements**
Day-to-day collective action	
MAR users have an arrangement of regular meetings in place to discuss the issues related to the operation and maintenance of the MAR system	Convening monthly meetings with the user group; Providing informal guidelines for the continuation of monthly meetings
There is a clear arrangement regarding who has access to the MAR site	Conducting household surveys to assess (i) willingness to join and (ii) household drinking water needs; Selecting 50 to 60 prospective households based on the outcome of the survey
There are rules in place regarding who can extract how much water, and when	Providing formal (written) and informal (verbal) instructions on MAR operation and maintenance
There is a mechanism in place to monitor MAR use and rule compliance	Setting up and running a monitoring system with users, and gradually handing it over to the community
There is a mechanism in place to punish rule breakers	Not found
There is a mechanism in place to hold monitor/s accountable to the MAR users.	Not found
There is a low-cost system in place to resolve conflict between users	Not found

Durable collective action	
All resource users understand the rules and policies guiding the management MAR	Conducting monthly meetings with user groups; organizing workshops with the user committee chairperson
General users – not only committee members – have the opportunity to participate at all levels of the decision-making process regarding MAR governance	Providing informal advice to the user committees; motivating user committees to include the general users in decision-making processes
MAR users have the technical and managerial skill and knowledge required to manage and operate the system	Training the caretaker; providing basic tools
There is a system in place to fairly allocate the benefits (e.g. water) and burdens (e.g. costs) associated with the resource among the users	Not found
The users have sufficient financial means to pay for the operation and maintenance of the MAR system	Assisting the user group in collecting community contributions (to cover operational costs and set up emergency funds); setting up a monthly payment structure; Providing material support
The users are willing to pay for the operation and maintenance of the MAR system	Motivating users through monthly meetings with them; informal household visits
All the users are aware of MAR, its operation and maintenance rules and the activities of the committee that is responsible for the management	Meetings at the Upazila (sub-district) premises involving local administrator, local government representatives, DPHE officials and local people; monthly meetings (i.e., tea stall meetings, yard meetings, mosque meetings) with the user group; Bi-weekly meetings with female users; bi-weekly sessions with teachers and students at educators; regular door-to-door visit to households; Handing out leaflets to local people; banners on MAR in the villages
Leadership is closely familiar with the changing external governance environment, has frequent interactions with all users and regular contact with local traditional leaders	Training the chairperson of the user committee; organizing workshops with committee chairpersons; connecting the user committee chairperson with local governments and agencies
The autonomy of users to manage their MAR system is not significantly undermined by any external authority	Advocacy and lobbying with external actors (i.e. Dhaka University MAR office, DPHE, local administration, and local government representatives, etc.)

Overall, our research suggests that NGO activities seem based on applying standard approaches to training and awareness raising, and less on empowering users to craft their own solutions.

HOW CAN DPHE ASSIST COMMUNITIES?

Evidence from our own and from earlier research suggests that the users of a drinking water system like MAR are less likely to abandon their drinking water system when there is a good relationship with the Department of Public Health and Engineering, DPHE. To give an example, we compared 30 rural drinking water systems in the southwestern coastal region of Bangladesh. Out of the 14 cases with strong internal collaboration, 11 (79%) reported to find the collaboration with DPHE helpful and meaningful. In contrast, out of the 16 cases with weak internal collaboration, only 5 (31%) reported to be satisfied with DPHE support.

How can DPHE officials best support community management? How can they best help communities to meet the criteria listed in chapter 2, above? Based on our research we suspect that the following aspects are crucial:

TABLE 5: REQUIREMENTS FOR COLLABORATION BETWEEN DPHE AND COMMUNITIES

Relationship between user group and public agency	
Trust	Mutual trust between DPHE and MAR users regarding the fulfilment of tasks and responsibilities
Communication	MAR users and DPHE communicate regularly
Institutional arrangements	
Inclusive decision-making	DPHE takes the opinion and interests of the user group into account
Clarity on tasks and responsibilities	The respective tasks and responsibilities of our user group and DPHE are clear and well-understood
transparency	Decision-making and operation of DPHE with regard to MAR is transparent

5. Site Selection Guidelines

INTRODUCTION

In order to develop strategies for MAR implementation in southwestern Bangladesh, insight is needed in which sites are potentially suitable. This chapter describes guidelines for the regional MAR site selection[5].

We suggest the following general approach to determine suitable regional locations for the implementation of MAR:

1. Determine the ***Social necessity*** for MAR. This need is assumed to exist when available drinking water options are insufficient, either from a quantitative or qualitative point of view;
2. Determine the ***Technical suitability*** for successful operation of MAR systems. This suitability is mainly based on hydrogeological characteristics, such as the presence of a suitable aquifer and the expected effect of density-driven flow of, and vulnerability to mixing with, brackish-saline groundwater;
3. Determine ***Potentially suitable locations*** based on combining the social necessity (1) and technical suitability (2) for MAR.

The methodology and outcomes in the form of guidelines for each of these 3 steps are presented below. These guidelines provide government agencies, NGO's and donors with a regional overview of:

- the social necessity for MAR (or alternative, similar techniques) as a safe drinking water option;
- potentially suitable locations for MAR implementation in southwestern Bangladesh.

It should be stressed that the identified areas on a regional scale are only *potentially* suitable. Due to high regional variability in hydrogeological characteristics, and a limited amount of available data on which the analyses are based, the identified locations should always be studied further on a local scale to determine whether the potential suitability in fact is a real actual suitability.

In the Annex directions are presented on how to apply the DeltaMAR site selection tool, which consists of a database and a GIS map generation and viewing system.

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[5] The guidelines for site selection are based on the methods and results described in the PhD Thesis of Floris Naus (Naus, F.L.(2020) Socio-hydrogeological Potential for Managed Aquifer Recharge in the Fresh-saline Aquifers of Southwestern Bangladesh).

DETERMINING THE SOCIAL NECESSITY FOR MAR

Methodology

The approach used to determine the social necessity for MAR is based on the following starting points:

1. It is assumed there is a social necessity for MAR when available drinking water options are either of insufficient quantity or quality;
2. We focused on the three most frequently used drinking water sources in the region: rainwater, pond water and groundwater:

- ***Rainwater* is considered unreliable and unsafe** as drinking water option. Although rainwater is generally of good quality, it is not available in sufficient quantity during the dry season. Rainwater Harvesting and storage may potentially solve this quantitative problem, but storage tanks can be bulky and costly, and the quality of the stored rainwater can deteriorate over time.
- ***Pond water* is considered unsafe** as drinking water option based on its biological water quality, as it is generally bacteriologically polluted and may cause diseases when used for drinking water.
- ***Groundwater* is considered biologically safe but may be unsafe from a chemical water quality perspective**. We considered the health effects of salinity and arsenic, using the chloride and arsenic concentrations of groundwater in the region. Groundwater is considered a safe drinking water option when the quality is within the Bangladesh drinking water standards (EC < 2 mS/cm, As < 0.05 mg/l).

Based on the above, we consider groundwater as the only potential source for safe drinking water. Based on groundwater quality we distinguished three social necessity classes for MAR:

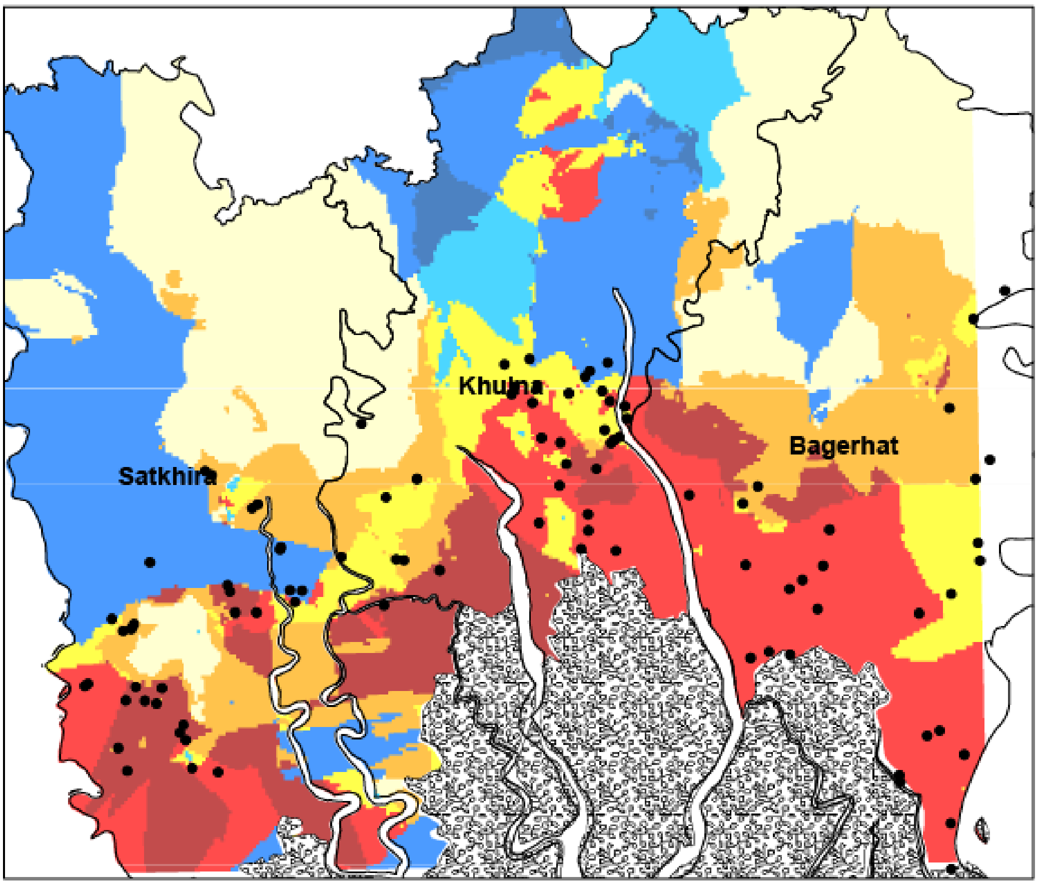
- **Low need** for MAR when either shallow or deep groundwater is of good quality with respect to salinity and arsenic, according to the Bangladesh drinking water standards. Deep tube wells are predominately placed on a communal level, so we assume they meet the drinking water standards.
- **High need** for MAR because of long term health problems, when shallow groundwater is brackish (2 < EC < 5 mS/cm) or is fresh but contains arsenic (As > 0.05 mg/l). We consider the long-term effects of brackish and arsenic water (Flanagan et al., 2012; Khan et al., 2014) to carry less of an immediate health risk than switching to pond water, as drinking pond water will likely result in more immediate health problems such as diarrhoea.
- **High need** for MAR because of short term health problems, when groundwater is saline (EC > 5 mS/cm). Saline groundwater is not palatable, and we expect people are then likely to resort to consumption of pond water, which is highly undesirable.

A database of groundwater quality indicators was compiled to obtain insight in (among others) chloride and arsenic contents. This database is compiled of data from previous studies, and unpublished data collected during multiple fieldwork campaigns between November 2015 and September 2018 (see Naus et al., 2019a; and Naus et al., 2019b). For salinity the electrical conductivity (EC) was used as a proxy. In total 2586 shallow (< 60 m deep), 303 intermediate deep (60-100 m) and 827 deep (>100 m) groundwater EC data points were used. For arsenic, the database consisted of 812 shallow (< 60 m) and 52 intermediate deep (60–100 m) measurements.

Groundwater quality maps of salinity and arsenic were made using Kriging to spatially interpolate concentrations on locations between measurement points. These maps were then overlaid in GIS to obtain the three social necessity classes for MAR in southwestern Bangladesh. We used both the EC and arsenic for the shallow to intermediate–deep (0–100 m) groundwater quality, but for the deep (> 100 m) groundwater quality we only considered the EC.

Guidelines for use of the Social Necessities map

The approach described above led to a map of the social necessity for MAR in southwestern Bangladesh, as displayed in Figure 9, below. The map can be used by government agencies, NGOs, donors and the like.



Legend

● Pilot MAR systems — Sundarbans

0 5 10 20 Kilometres

Necessity for MAR	Shallow and intermediate deep		Deep	
	EC (mS/cm)	As (µg/l)	EC (mS/cm)	As (µg/l; assumed)
Low	< 2	< 50	< 2	< 50
Low	> 2	> 50	< 2	< 50
Low	< 2	< 50	> 2	< 50
High, long term	< 2	> 50	> 2	< 50
High, long term	> 2, < 5	< 50	> 2	< 50
High, long term	> 2, < 5	> 50	> 2	< 50
High, short term	> 5	< 50	> 2	< 50
High, short term	> 5	> 50	> 2	< 50

FIGURE 9: SPATIAL DISTRIBUTION OF THE SOCIAL NECESSITY FOR MAR AS A FUNCTION OF OBSERVED GROUNDWATER QUALITY, USING THE BANGLADESH DRINKING WATER STANDARDS FOR SALINITY (EC) AND ARSENIC (AS) AS INDICATORS**.**

Guidelines for use of the map are summarized in Table 6

TABLE 6: GUIDELINES FOR USE OF THE SOCIAL NECESSITY MAP

Social Necessity for MAR	**Explanation**
Low need	Groundwater in these areas is of sufficient quality as to their salinity or arsenic concentrations
High need, because of long term health problems	In these areas: • Shallow groundwater is either Brackish or exceeding Arsenic drinking water standards • Deep groundwater is Brackish
High need, because of short term health problems	In these areas: • Shallow groundwater is Saline, and in some areas also exceeds Arsenic drinking water standards • Deep groundwater is Saline
Limitations	**Explanation**
Delineation of the map areas is not precise	This is due to: • the limited amount of groundwater quality data available used to construct the map; • the fact that groundwater quality in the area is highly variable; • interpolation between data points, using Kriging;
Only 2 parameters used for drinking water quality	Only EC (as an indicator for salinity) and arsenic are used to determine groundwater quality
Drinking water habits are hard to break	The attachment of people to unsafe drinking water habits is stronger than what one might be inclined to think, also in the 'high need' category. Awareness raising activities need to take that into consideration: • In order to wean households off pond water, and have them switching to (e.g.) MAR, it is recommended to focus awareness raising campaigns on the risk and inconvenience of drinking pond water. • The largest potential for getting shallow tube well users to adopt alternative, safe options is to focus on the risk associated with drinking groundwater with elevated levels of arsenic or salinity.

Given the restrictions indicated in the table above, the map only provides a first indication of areas with/without a need for safe drinking water options such as MAR (or alternative techniques). Before actual implementation on a *local* site scale, additional checks should be performed as to the actual groundwater quality.

ALMOST HALF OF THE POPULATION OF BANGLADESH HAS NO ACCESS TO GOOD QUALITY DRINKING WATER

DETERMINING THE TECHNICAL SUITABILITY FOR MAR

Methodology

The approach used to determine the technical suitability for MAR is based on the following starting points:

1. We *excluded areas* where MAR implementation is not feasible:
   - the protected Sundarbans mangrove area;
   - often-inundated aquaculture ponds;
   - (tidal) river and floodplains that are regularly flooded.
2. MAR requires a *suitable aquifer* for underground water storage. We assumed a suitable target aquifer had to be:
   - present within manual drilling range (up to 60 m deep) to keep the costs of installation acceptable;
   - at least 30 feet (9.1 m) thick, to allow sufficient storage capacity.
3. MAR *water quality should be in conformance with Bangladesh drinking water standards*. Arsenic and salinity were used as relevant indicators for drinking water quality.
4. The performance of a MAR system should show a sufficient *Recovery Efficiency (RE) of at least 60%*. Recovery Efficiency is defined as the percentage of infiltrated water that can be recovered while maintaining sufficient drinking water quality. Recovered MAR water may deteriorate by mixing with native groundwater that contains high salinity or arsenic concentrations. Density driven flow due to high salinity may also negatively affect recovered MAR water quality.

Based on these starting points, maps were made of the effects of:

- density driven flow;
- the vulnerability to mixing with native groundwater, taking salinity and arsenic as indicators for drinking water quality.

These maps were then combined into a Technical Suitability map[6].

GUIDELINES FOR USE OF TECHNICAL SUITABILITY MAP

Presence of a suitable aquifer

The Kriging interpolation map of aquifer thickness based on 875 borehole logs indicates that over the whole region suitable aquifers occur that are thicker than the formulated minimum requirement of 9.1 m (30 ft), within the first 60 m. Thus aquifer thickness is not a significant constraint for MAR implementation.

Nonetheless, 48 borehole logs (ca. 5%) indicate that local aquifer thickness may be less than 30 ft, but these locations are obscured on the map due to Kriging interpolation.

This reveals that:

- on a *regional* scale we can assume suitable aquifers are present throughout;
- however, at the *local* scale it should be checked whether aquifer thickness is indeed at least 30 ft, e.g. by using a test drilling.

Technical Suitability Index

Figure 10 presents the Technical Suitability Index on the regional scale of southwest Bangladesh. The darker colors indicate suitable areas. The lighter areas are technically less suited for MAR implementation. The map may be used by government agencies, NGO's, donors and the like, to identify on the regional scale of the districts of Satkira, Khulna and Bagherat.

[6] For a full description of the methodology of constructing these maps see Naus (2020).

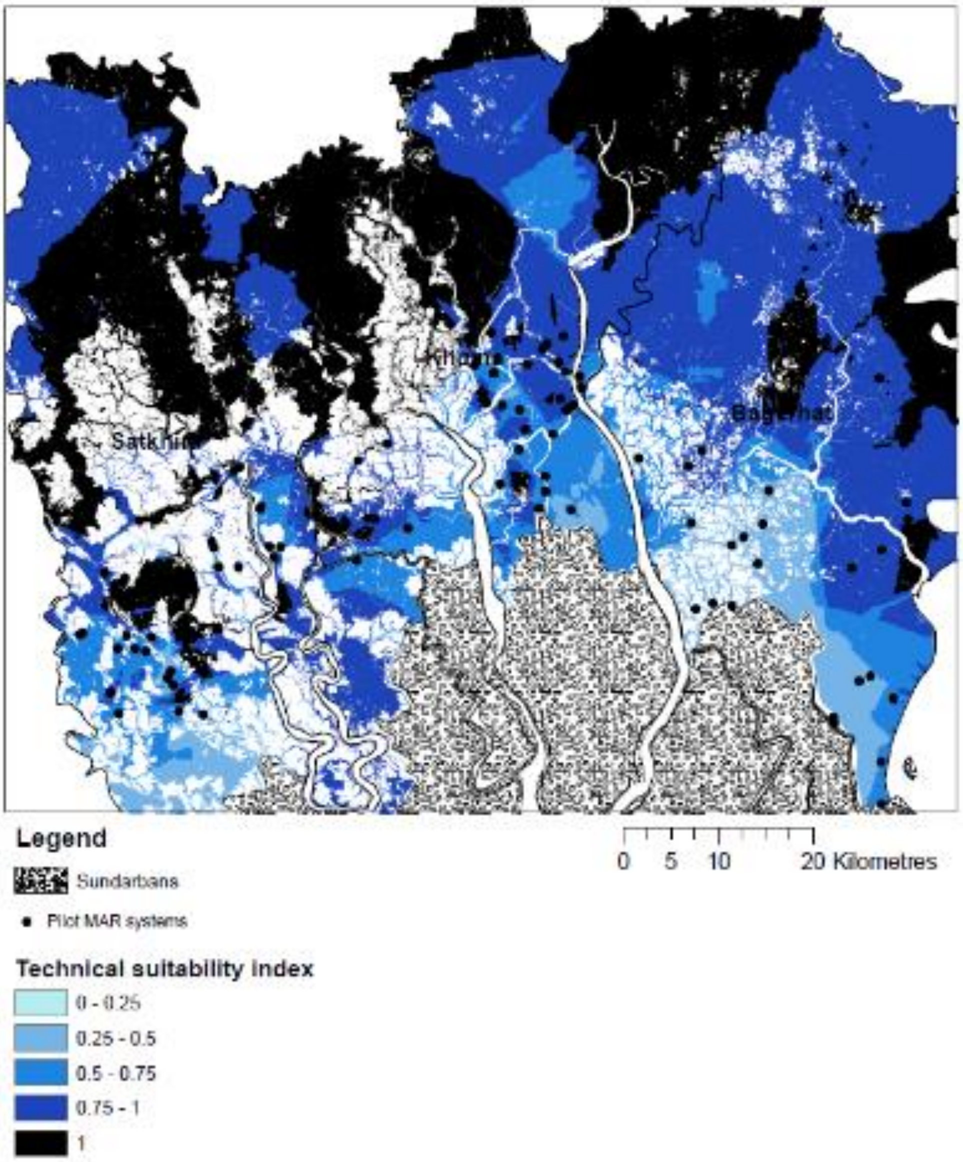


FIGURE 10: TECHNICAL SUITABILITY INDEX FOR MAR THROUGHOUT THE STUDY REGION. THE LOWER THE INDEX VALUE, THE LOWER THE EXPECTED TECHNICAL PERFORMANCE OF THE MAR SYSTEMS, I.E. A HIGHER CHANCE OF INSUFFICIENT MAR WATER QUALITY.

Table 7 presents guidelines on the use of the map.

TABLE 7: GUIDELINES FOR USE OF THE TECHNICAL SUITABILITY MAP

Map areas	**Technical suitability for MAR**
Index = 1	**Highly suitable:** no MAR water quality deterioration expected from mixing with native groundwater
Index < 1	**Decreasing suitability with lower index:** the lower the index, the higher the likelihood of deterioration of MAR water quality due to: • mixing with brackish-saline or arsenic containing native groundwater • and/or density driven flow
White areas	**Not suitable** because of current land use (frequently flooded areas, aquaculture areas, Sundarbans)
Limitations	**Explanation**
Local scale differences	At the local scale it should always be checked whether an aquifer is present of sufficient thickness of at least 30 ft (9.1 m), e.g. by using a test drilling (because ca. 5% of boreholes show insufficient aquifer thickness)
Recovery Efficiency	The technical suitability is based on a minimum Recovery Efficiency of 60%. One could argue however that in areas with high social necessity, every amount of recoverable safe groundwater may help to fulfill people's drinking water needs, even if the RE is lower than 60%. This would imply considerably more fresh water is needed for infiltration than what will be finally recovered for safe use. Thus enough fresh water (e.g. unsafe pond water) should be available for infiltration.

DETERMINE THE REGIONAL MAR POTENTIAL

Methodology

The Regional MAR potential has been determined by combining in a GIS system the map of the Social Necessity for MAR, with the map of the Technical Suitability for MAR based on hydrogeological characteristics.

Guidelines for use of the Regional MAR potential map

The resulting map for Regional MAR potential is presented in figure … and may be used to identify on the regional scale which areas:

- have a medium or high *need* for MAR (or alternative safe drinking water option)
- are *suitable* for MAR implementation, from a hydrogeological point of view
- show *highest potential* for MAR implementation (darker areas)

The Regional MAR potential is highest in areas where both social necessity and technical suitability are high. However, there are few such areas; there appears to be a mismatch between the technical suitability and the social necessity for MAR:

- In areas with a *high technical suitability* index, the need for MAR is usually lacking or low. These areas are mainly found in the northern part of the study area, where groundwater is of good quality.
- In contrast, in areas with a *high social necessity* for MAR the technical suitability index is often below 0.75 or even below 0.5. These areas are mostly in the south of the region, near the Sundarbans. This stems from the fact that in the south groundwater is often brackish or saline which implies:
  - social necessity for fresh drinking water quality is large;
  - but at the same time MAR systems are more vulnerable to water quality deterioration, due to density driven flow and mixing with brackish-saline water

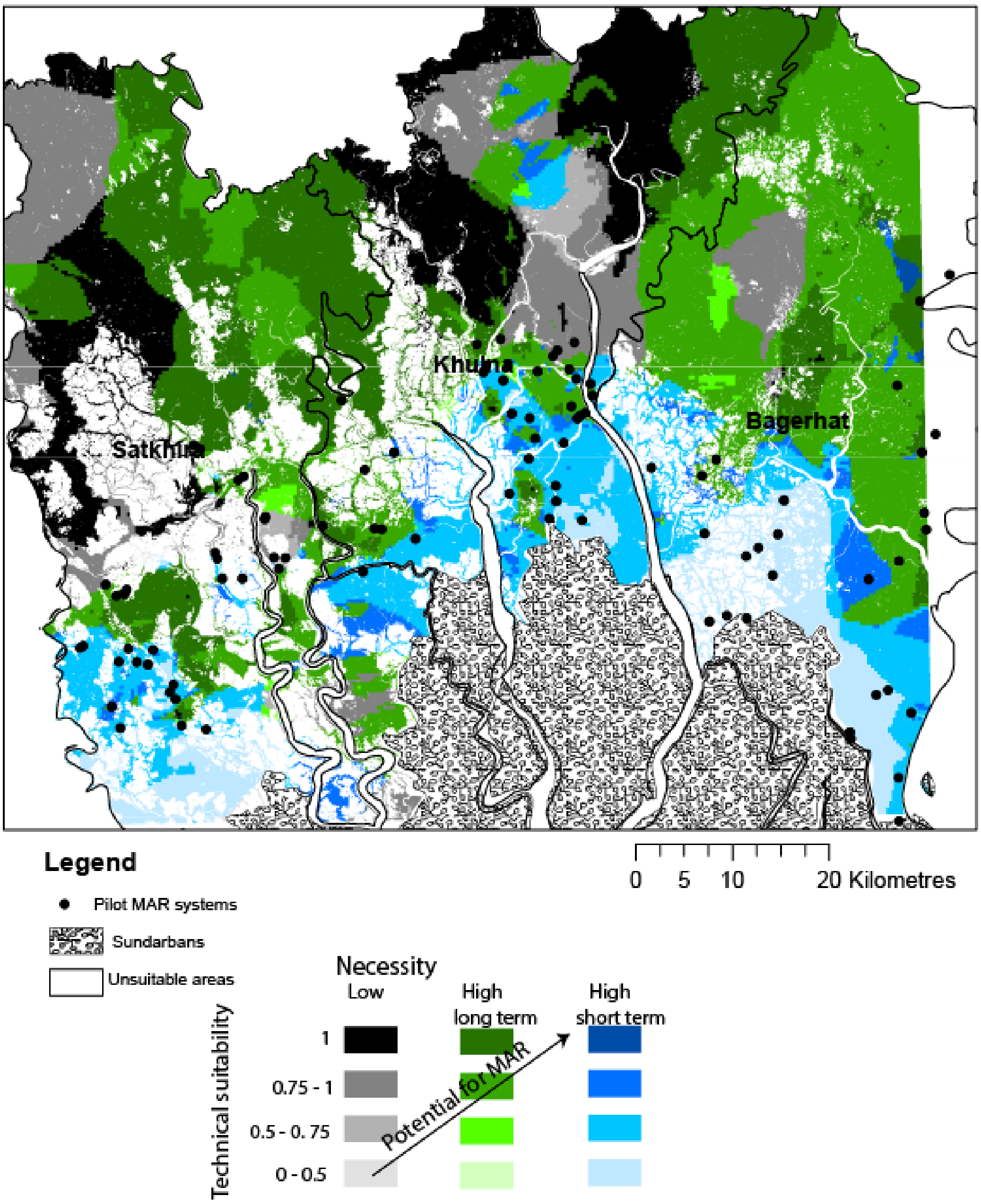


FIGURE 11: REGIONAL MAR POTENTIAL. THE MAP IS A COMBINATION OF THE SOCIAL NECESSITY MAP AND THE TECHNICAL SUITABILITY INDEX MAP. THE HIGHER THE SOCIAL NECESSITY AND TECHNICAL SUITABILITY INDEX, THE HIGHER THE POTENTIAL FOR MAR (DARKER COLORS).

The MAR Potential map reveals the areas where MAR may be applied to establish safe drinking water supply. As such it may be used by government agencies, NGOs, donors and the like to develop a regional water resource management strategy. Guidelines for use are presented in Table 8.

TABLE 8: GUIDELINES FOR USE OF THE REGIONAL MAR POTENTIAL MAP

Social necessity	Technical suitability	MAR Potential
High, because of short term health problems	**Low**	MAR systems are unlikely to function optimally because of high groundwater salinity and associated mixing with native saline groundwater. Nevertheless, MAR can still be an option for providing safe drinking water by infiltrating more fresh (pond) water than is finally extracted (see figure 12 below for needed infiltration capacity). Although this will lead to a lower Recovery Efficiency, it will still provide valuable safe drinking water. In such cases it is recommended to make large village/community level MAR systems, to minimize relative losses due to mixing with polluted native groundwater. A prerequisite for such larger systems is that sufficient fresh source water is available for MAR infiltration.
High, because of long term health problems	**High**	MAR systems have potential to solve the current drinking water problems related to consumption of groundwater with unacceptable levels of arsenic or salinity.
Low		In areas without a current safe drinking water need, MAR could still become relevant in the future as a sustainable water option when groundwater resources are overexploited

Restrictions to consider	Explanation
Methodological assumptions and generalizations	For instance: • Rainwater and pond water are assumed to be unreliable and/or unsafe as drinking water options. This makes that the social necessity for MAR is based solely on groundwater quality. There is a need for MAR only in those areas where groundwater quality does not comply with Bangladesh drinking water standards. • Only salinity (EC) and arsenic concentrations were considered to define safe drinking water quality; • MAR is only possible with at least 30 ft (9.1 m) aquifer thickness within 60 m depth; • Interpolation of different types of point data by Kriging
High hydrogeological variability and limited data	This implies the identified locations should always be studied further on a local scale to check the indicated MAR potential

Other important factors	MAR Potential presented is based on social necessity for safe drinking water and technological suitability from a hydrogeological point of view. There are several other factors that determine whether this potential can be turned into successful MAR operation, such as MAR design and maintenance, sufficient fresh water to infiltrate (e.g. pond water and/or rainwater), monitoring of MAR water quality, governance of the MAR, etc.

Note that the presented MAR potential map results from the approach discussed above. Other approaches may be equally valid leading to different patterns of MAR potential. The DeltaMAR site selection tool (appendix 1) may be used to examine how different approaches may lead to different spatial MAR potential patterns. This may help to analyze how sensitive the results are to the different approaches using different parameters.

Guidelines for areas with high short term social necessity but low technical suitability

It is important to realize that in areas with a low Technical Suitability, MAR may still be an option to provide safe drinking water. This is especially important as these are often areas where the short term social necessity for MAR is high.

In such areas MAR may be employed by ‘over-infiltrating’ fresh water compared to areas with a higher technical suitability. This extra infiltration water will experience deterioration with respect to water quality at the edge of the infiltration bubble due to mixing. But this zone will also serve as a buffer for the core of the MAR infiltration water that is kept free from water quality deterioration and can thus be safely recovered.

Figure 12 indicates the amounts needed for MAR infiltration to achieve proper technical functioning.

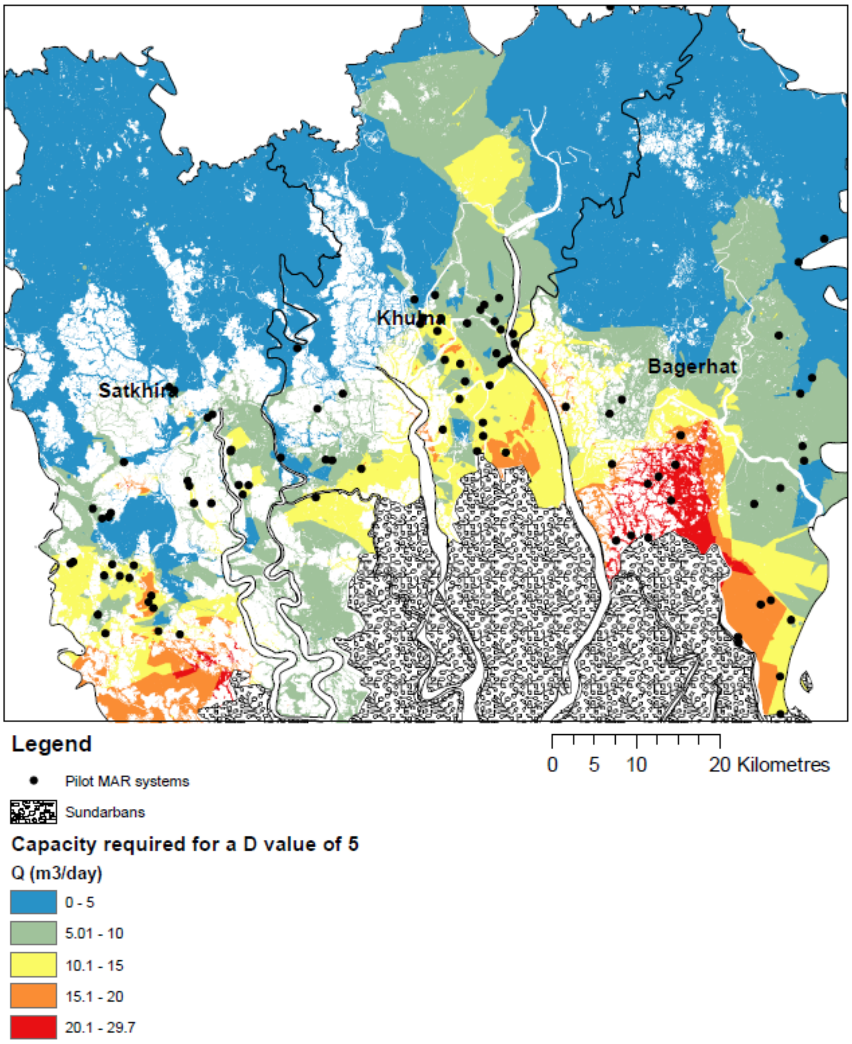


FIGURE 12: REQUIRED AVERAGE INFILTRATION PER DAY TO ACHIEVE A D VALUE OF 5, CORRESPONDING WITH A RECOVERY EFFICIENCY OF APPROXIMATELY 60%.

Table 9 presents guidelines on how to use the map. It is based on the observation that MAR systems in the south can produce good quality water but do so less efficiently than systems in the north.

TABLE 9: GUIDELINES FOR USE OF THE MAP OF REQUIRED INFILTRATION PER DAY

Infiltration capacity	Areas
Q= 5	In the areas with high technical suitability an infiltration capacity of less than 5 m^3/day is sufficient (blue)
Q > 5	In areas with lower technical suitability higher infiltration rates are needed to attain sufficiently working systems that produce sufficient safe drinking water; infiltration rates become increasingly higher towards some areas in the south

References

Hasan, M. B., Driessen, P. P., Majumder, S., Zoomers, A., & van Laerhoven, F. (2019). Factor Affecting Consumption of Water from a Newly Introduced Safe Drinking Water System: The Case of Managed Aquifer Recharge (MAR) Systems in Bangladesh. *Water*, 11(12), 2459.

Hasan, M. B., Driessen, P., Zoomers, A., & Van Laerhoven, F. (2020). How can NGOs support collective action among the users of rural drinking water systems? A case study of Managed Aquifer Recharge (MAR) systems in Bangladesh. *World Development*, 126, 104710.

Hasan, M.B., Driessen, P., Zoomers, A., Majumder, S., van Laerhoven, F. (resubmission awaiting). A community management plus model for the governance of rural drinking water systems: A comparative case study of Pond Sand Filter (PSF) systems in Bangladesh. *International Journal of the Commons*

Hasan, M.B., Driessen, P., Zoomers, A., Majumder, S., van Rijnsoever, F., van Laerhoven, F. (to be submitted soon). Elucidating consumer drinking water preferences. A choice experiment in Southwestern Bangladesh.

Hasan, Mohammad Imran; Ahmed, Kazi Matin; Rietveld, L. C.; van Breukelen, Boris M.; Bakker M. (to be completed a). Assessment of aquifer storage and recovery efficiency in coastal aquifers

Hasan, Mohammad Imran; Rafiq, Muhammad Risalat; Ahmed, Kazi Matin; Rietveld, L. C.; van Breukelen, Boris M. (to be completed b). ASTR modelling of MAR system with variable salinity distribution in SW Bangladesh

Hutchings, P., Chan, M. Y., Cuadrado, L., Ezbakhe, F., Mesa, B., Tamekawa, C., & Franceys, R. (2015). A systematic review of success factors in the community management of rural water supplies over the past 30 years. *Water Policy*, *17*(5), 963-983.

Naus, F.L., 2020. Socio-hydrogeological Potential for Managed Aquifer Recharge in the Fresh-saline Aquifers of Southwestern Bangladesh, Ph.D. thesis. Utrecht University.

Naus, F. L., Burer, K., van Laerhoven, F., Griffioen, J., Ahmed, K. M., & Schot, P. (2020). Why do people remain attached to unsafe drinking water options? Quantitative evidence from Southwestern Bangladesh. *Water*, 12(2), 342.

Naus, F. L., Schot, P. P., Ahmed, K., & Griffioen, J. (2019a). Groundwater salinity variation in Upazila Assasuni (southwestern Bangladesh), as steered by surface clay layer thickness, relative elevation and present-day land use. *Hydrology and Earth System Sciences*, 23(3), 1431-1451.

Naus, F.L., 2020. Socio-hydrogeological Potential for Managed Aquifer Recharge in the Fresh-saline Aquifers of Southwestern Bangladesh, Ph.D. thesis. Utrecht Universiteit

Naus, F. L., Schot, P., Ahmed, K. M., & Griffioen, J. (2019b). Influence of landscape features on the large variation of shallow groundwater salinity in southwestern Bangladesh. *Journal of Hydrology X,* 5, 100043.

Naus, F.L., Schot, P., van Breukelen, B.M., Ahmed, K.M, Griffioen, J. (to be submitted soon). Potential for Managed Aquifer Recharge in southwestern Bangladesh based on social necessity and technical suitability

Rafiq, Muhammad Risalat; Ahmed, Kazi Matin; van Breukelen, Boris M. (to be completed a) Monitoring and mass balance modelling of Hydrogeochemical processes governing MAR water quality in SW Bangladesh

Rafiq, Muhammad Risalat; Ahmed, Kazi Matin; van Breukelen, Boris M. (to be completed b). Hydrogeochemical processes (im)mobilizing trace metals in MAR for drinking water provision: a case study in SW Bangladesh.

Rafiq, Muhammad Risalat; Hasan, Mohammad Imran, Ahmed, Kazi Matin; Rietveld, L. C.; van Breukelen, Boris M. (to be completed c). Identification of MAR archetypes through statistical and time trend analysis on basis of hydro-chemical data from 99 UNICEF MAR sites, SW Bangladesh

Tolk, L., Tuinhof, A., te Winkel, T., Matin Ahmed, K., Bolton, M. (2014). Underground freshwater storage – A practical solution to increase water security in saline deltas. Acacia Water, Gouda

Annex 1.
Using the DeltaMAR site selection tool

INTRODUCTION

The Regional site selection guidelines described above are based on maps produced with the DeltaMAR site selection tool. The aim of this tool is to help identify the suitability of a specific location for the installation of a MAR system. Alternatively, the tool may be used on a more regional scale to indicate where to find promising locations.

The DeltaMAR site selection tool basically consists of the following components:

- A database (Excel) with information on groundwater wells, their location, filter depth, and groundwater quality;
- A GIS map viewer (ArcGIS, or a non-commercial free-ware equivalent) which enables to display the spatial distribution of the data from the database (e.g. as interpolated maps using Kriging)

The intended users of the site selection tool are primarily Bangladeshi government agencies responsible for drinking water provision, such as the DPHE and the Bangladesh Water Development Board (BWDB). Due to probable inaccuracies at local level as mentioned above, the tool is best suited for application at regional scale. At local scale the amount of nearby data points needs to be specifically taken into consideration to get an impression of the perceived accuracy of the indicated MAR suitability.

It is important to be aware from the start that the reliability of the tool depends heavily on the amount of data present in a particular area. Since both geology (sand and clay layers) as well as groundwater quality (e.g. salinity and arsenic concentrations) in Southwestern Bangladesh shows large variations at short distances this may influence the reliability of the produced (interpolated) maps.

THE DATABASE

The database of the DeltaMAR site selection tool contains the following data:

- Geological data
- Groundwater quality data

Geological database

The geological database consists of ca. 4400 borehole data.

It includes data on the location of a borehole, depth of the filters, lithological information, etc.[7]. Figure 13 presents a screenshot of the database.

Bore	Depth1	Depth2	Lithology	Longitude	Latitude	Easting	Northing	Elevation	TD	Symbol	Color	GEIcon
KHBGLW1	0	45,73	Clay	90,5183	22,7377	861410	2518773	6	57,93	2	12	
KHBGLW1	45,73	57,93	Sand1	90,5183	22,7377	861410	2518773	6	57,93	2	12	
KHBGLW1	0	24,39	Clay	89,5128	22,7364	758075	2516530	6	85,37	2	12	
KHBGLW1	24,39	85,37	Sand1	89,5128	22,7364	758075	2516530	6	85,37	2	12	
KHBGLW1	0	30,49	Clay	89,503	22,7332	757066	2516154	6	85,37	2	12	
KHBGLW1	30,49	85,37	Sand1	89,503	22,7332	757066	2516154	6	85,37	2	12	
KHBGLW1	0	9,15	Clay	89,4932	22,7313	756064	2515923	6	91,46	2	12	
KHBGLW1	9,15	91,46	Sand1	89,4932	22,7313	756064	2515923	6	91,46	2	12	
KHBGLW1	0	12,2	Clay	89,4824	22,7336	754950	2516168	6	91,46	2	12	
KHBGLW1	12,2	91,46	Sand1	89,4824	22,7336	754950	2516168	6	91,46	2	12	
KHDKLW1	0	24,39	Clay	89,5229	22,6056	759354	2502052	6	85,37	2	12	
KHDKLW1	24,39	85,37	Sand1	89,5229	22,6056	759354	2502052	6	85,37	2	12	
KHDKLW2	0	30,49	Clay	89,5131	22,6051	758344	2501988	6	85,37	2	12	
KHDKLW2	30,49	85,37	Sand1	89,5131	22,6051	758344	2501988	6	85,37	2	12	
KHDKLW3	0	24,39	Clay	89,5086	22,6057	757885	2502040	6	85,37	2	12	
KHDKLW3	24,39	85,37	Sand1	89,5086	22,6057	757885	2502040	6	85,37	2	12	
KHDKLW4	0	18,29	Clay	89,5019	22,6068	757191	2502151	6	88,41	2	12	
KHDKLW4	18,29	39,63	Sand1	89,5019	22,6068	757191	2502151	6	88,41	2	12	
KHDKLW4	39,63	45,73	Clay	89,5019	22,6068	757191	2502151	6	88,41	2	12	

FIGURE 13: SCREENSHOT OF THE ECOLOGICAL DATABASE.

Groundwater quality database

The groundwater quality database consists of approximately 9,700 groundwater quality analysis.

It includes data on the location, depth and sampling date and one or more water quality parameters[8]. Figure 14 presents a screenshot of the database.

FID	Data_source	date	Lat	Long	Depth_ft	Depth_m	EC	Temperat	pH	Eh	Arsenic	HCO3 mg/	DO mg/l	DO%	ORP	Source_D	Notes
1	Abir_nov_2017	08.11.17	22,5615	89,0953	470	143,256	1,1	28,1									Drinking & washing
2	Abir_nov_2017	08.11.17	22,5611	89,0963	490	149,352	2,06	27,7									Drinking & washing
3	Abir_nov_2017	08.11.17	22,561	89,0961	480	146,304	1,69	27,6									Drinking & washing
4	Abir_nov_2017	08.11.17	22,6966	89,075	145	44,196	0,98	27,7									Drinking
5	Abir_nov_2017	08.11.17	22,6966	89,0744	460	140,208	0,87	27,6									Drinking
6	Abir_nov_2017	08.11.17	22,6951	89,0719	490	149,352	1,08	27,9									Drinking
7	Abir_nov_2017	08.11.17	22,6996	89,0744	960	292,608	2,43	27,5									Drinking
8	Abir_nov_2017	08.11.17	22,686	89,0536	720	219,456	0,92	28,1									Drinking
9	Abir_nov_2017	08.11.17	22,686	89,0537	680	207,264	1,11	27,6									Drinking
10	Abir_nov_2017	08.11.17	22,6858	89,0537	100	30,48	2,25	28,1									Washing
11	Abir_nov_2017	08.11.17	22,6855	89,0537	160	48,768	2,37	27,6									Washing
12	Abir_nov_2017	08.11.17	22,684	89,0534	145	44,196	2,28	27,7									Washing
13	Abir_nov_2017	08.11.17	22,6822	89,0526	700	213,36	1,27	27,7									Drinking
14	Abir_nov_2017	08.11.17	22,6821	89,0527	100	30,48	1,15	26,9									Washing
15	Abir_nov_2017	08.11.17	22,6807	89,0528	770	234,696	1,39	27,7									Drinking
16	Abir_nov_2017	08.11.17	22,6801	89,0524	70	21,336	1,32	27,2									Drinking & washing
17	Abir_nov_2017	08.11.17	22,6785	89,0564	140	42,672	1,55	27,6									Washing
18	Abir_nov_2017	08.11.17	22,6784	89,0559	100	30,48	1,47	27,2									Washing
19	Abir_nov_2017	08.11.17	22,6782	89,0559	140	42,672	1,48	26,8									Washing
20	Abir_nov_2017	08.11.17	22,6765	89,0574	760	231,648	1,33	27									Drinking
21	Abir_nov_2017	08.11.17	22,6743	89,057	185	56,388	1,76	27,4									Washing
22	Abir_nov_2017	08.11.17	22,6747	89,0571	680	207,264	1,34	26,9									Drinking
23	Abir_nov_2017	08.11.17	22,6714	89,061	760	231,648	1,31	27,1									Drinking

FIGURE 14: SCREENSHOT OF THE GROUNDWATER QUALITY DATABASE (WITH ELECTRICAL CONDUCTIVITY HIGHLIGHTED).

[7] For additional information see Naus (2020).

[8] For additional information see Naus (2020).

THE GIS MAP VIEWER

The spatial distribution of the data from the database may be presented on maps using a GIS map viewer, such as ArcGIS. GIS offers possibilities of presenting maps of the variables in the database, e.g.:

- Single variables, such as the well locations and identification numbers, Electric conductivity, arsenic concentration
- A selection of variables according to certain predefined constraints, such as Chloride concentrations > 1000 mg/l, etc.
- Combined variables, such as all location where EC > 2000 and filter depth < 60m.

In this way users are free to select the information from the database as wanted for their specific purpose. Figure 15 below presents some examples of maps generated with GIS from the groundwater quality database.

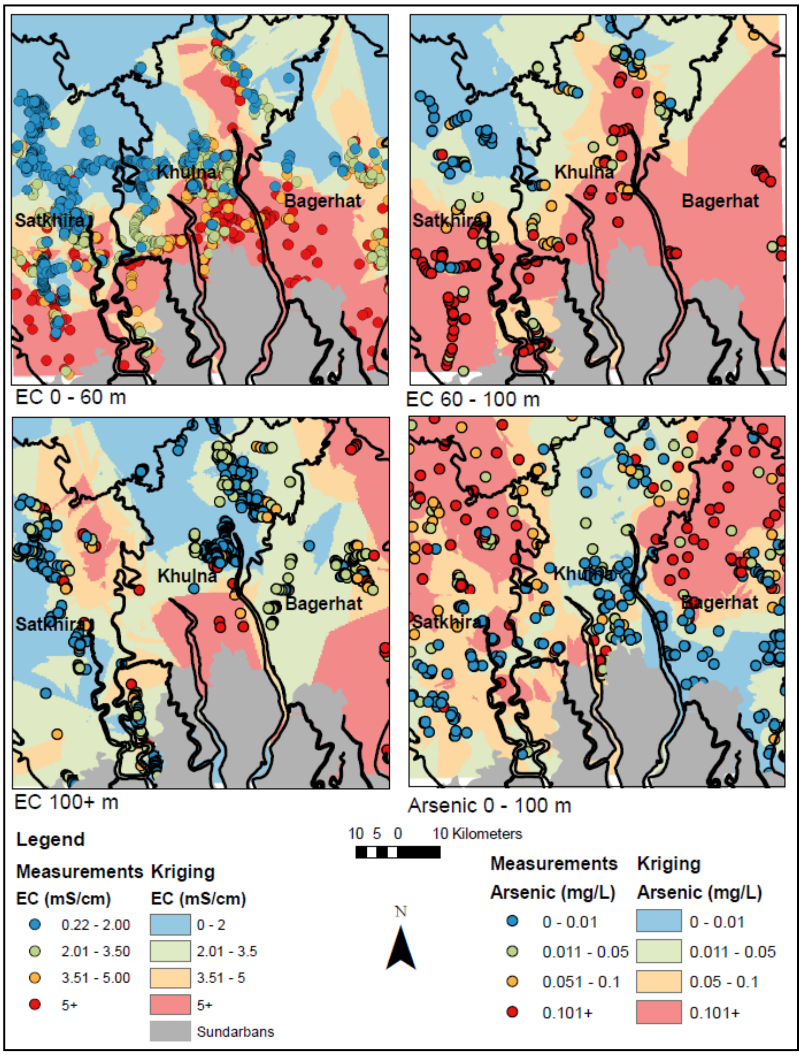


FIGURE 15: EXAMPLE OF ARCGIS MAP VIEWER RESULTS USING A SELECTIONS OF VARIABLES (EC AND ARSENIC) ACCORDING TO CERTAIN CONSTRAINTS (DEPTH INTERVAL).

HOW TO USE THE SITE SELECTION TOOL

In general the following steps may guide users of the tool to obtain the information wanted[9].

- *Step 1. Determine aim of the selection*
- *Step 2. Determine geographic window*
- *Step 3. Select the variables needed, or a combination of variables and constraints*
- *Step 4. Plot them*
- *Step 5. Interpolate point data to create polygons (e.g. Kriging interpolation)*

FUTURE IMPROVEMENTS

As new data come available in future, the existing geological and groundwater quality data may be enlarged. This is especially important in southwestern Bangladesh as hydrogeological characteristics (lithology, groundwater quality) show large spatial variation. This will allow user to benefit from as much data as possible when looking at the regional scale, or at a certain local site for implementing MAR.

Keeping the databases updated implies that some organization should take responsibility for this.

[9] For detailed information on how to use the GIS map viewer one is referred to the respective software manual.

Annex 2.
Research outputs – findings and recommendations[10]

Research output	Research design and methods	Main findings	Recommendations
OUTPUT RELATED WITH FRESH WATER RECOVERY			
Hasan, Mohammad Imran; Rafiq, Muhammad Risalat; Ahmed, Kazi Matin; Rietveld, L. C.; van Breukelen, Boris M. (to be completed). ASTR modelling of MAR system with variable salinity distribution in SW Bangladesh	• A median base case was simulated with median parameter from 99 MAR site. • This base case is used to simulate different scenario.	• Fresh water movement in the saline water is lower at the central abstraction zone • The formation of a freshwater bubble takes time and depends on the number of injection wells • Longer abstraction wells increase MAR recovery	• **Increase infiltration frequency** to get higher recovery efficiency • **Create longer abstraction wells** to increase recovery efficiency
Hasan, Mohammad Imran; Ahmed, Kazi Matin; Rietveld, L. C.; van Breukelen, Boris M.; Bakker M. (to be completed). Assessment of aquifer storage and recovery efficiency in coastal aquifers	We developed a new tool for creating optimal recovery efficiency	• The new tool is more time efficient • We find that storage period tends to decrease recovery efficiency.	• We recommend the use of our tool to **assess the recovery efficiency prior the implementation** of MAR.

[10] Links to the project publications can be found on the DeltaMAR website.

OUTPUT RELATED WITH WATER QUALITY			
Rafiq, Muhammad Risalat; Hasan, Mohammad Imran, Ahmed, Kazi Matin; Rietveld, L. C.; van Breukelen, Boris M. (to be completed). Identification of MAR archetypes through statistical and time trend analysis on basis of hydro-chemical data from 99 UNICEF MAR sites, SW Bangladesh	***Objective:*** To identify and group similar MAR sites based on physical and hydro-chemical processes like salinity reduction and concentration of As, Fe, etc. to potentially identify factors that cause these differences. ***Approach:*** Python-pandas scripting was developed to read and plot results of the 99 MAR sites dataset. Linear trend analysis was applied to assess temporal patterns in As and Fe concentrations. Scatter plots (correlation between As/Fe), principal component analysis, and cluster analysis were done to find groups of similarly performing sites. Descriptive statistical analysis was performed to calculate mean and median values and then spatial maps with those values were prepared using ArcGIS® software.	Sites are identified with (i) decreasing As and Fe concentrations with high starting values, (ii) increasing As and Fe concentration with low starting values, and (iii) increasing As and Fe concentrations with high starting values	Based on these results, sites for further detailed study were selected
Rafiq, Muhammad Risalat; Ahmed, Kazi Matin; van Breukelen, Boris M. (to be completed) Monitoring and mass balance modelling of Hydrogeochemical processes governing MAR water quality in SW Bangladesh	***Objective:*** Identification of key hydro-geochemical processes at two MAR sites ***Approach:*** Detailed monitoring and mass balance modeling. Water samples were collected with onsite parameters and lab analyses data were processed to get mass balance model (PHREEQC).	• Aerobic fresh infiltration water mixes with anaerobic brackish native groundwater • Consumption of O_2 by dissolved Fe^{2+} that subsequently precipitated as $Fe(OH)_3$ at GMF11, and by dissolved and sedimentary organic matter at site JJS91 • Reduction of SO_4 coupled to oxidation of OM at both sites; • Mixing corrosion and freshening/ salinization induced cation-exchange (Ca sorption; Na desorption at GMF11 and vice versa at JJJS91) • Arsenic mobilization is only temporal, and its concentration will lower when the system has been flushed more frequently.	• Issue proper operational management instructions that regard **flushing to yield better recovery with permissible drinking water standards**

Rafiq, Muhammad Risalat; Ahmed, Kazi Matin; van Breukelen, Boris M. (to be completed). Hydrogeochemical processes (im)mobilizing trace metals in MAR for drinking water provision: a case study in SW Bangladesh.	***Objective***: To observe aquifer reactivity in response to freshwater injections focusing on trace metals (im)mobilizations. ***Approach:*** Aerobic (cyclic) and anaerobic (sucrose amended) Push Pull Tests (PPTs) were conducted at selected MAR sites to	• O_2 leads to oxidation of mostly dissolved and desorbed Fe from clay and SOM; • Formation of Fe oxides leads to removal of trace metals like As, Mn and Fe • Strong increase of Fe, Mn and As were observed with sucrose addition that indicate Reductive dissolution of Fe(III)oxides	• Issue proper operational management instructions that regard **creating a freshwater bubble that is more oxic in order to immobilize trace metals at MAR sites**
OUTPUT RELATED WITH GOVERNANCE			
Hasan, M.B., Driessen, P., Zoomers, A., Majumder, S., van Rijnsoever, F., van Laerhoven, F. (to be submitted soon). Elucidating consumer drinking water preferences. A choice experiment in Southwestern Bangladesh.	***Theory/Framework***: Preferences for drinking water delivery systems were measured through scenarios based on 4 attributes (i.e. disaster resilience, health risk, reliability of water availability, and taste) and 3 levels (low, medium, high). ***Study sites***: 16 communities, in7 sub-districts, in 3 districts ***Research methods***: Research design was based on a choice experiment. Household surveys (using choice cards) (N=882) were used for data collection. Logit regression was used for analysis	• Households in the study area value drinking water delivery systems that are cyclone proof, do not make them sick, that provide drinking water reliably all year round, and that produce water that tastes good. • More than anything else, households are willing to pay more for drinking water delivery systems that is free of health risks. • Poor(er) households especially value safe drinking water from a reliable source.	• Before the introduction of a new drinking water delivery system establish in detail what **community preferences** are. • Communities value systems that are **cyclone proof, and that provide safe, tasty water reliably**. Guarantee that the system you are promoting offers all that. • In your attempt to have households adapting your new system, **raise awareness based on an explicit narrative** that stresses its performance with specific regard to these attributes. • When working with poor households, **focus on health and reliability features** in particular.
Hasan, M. B., Driessen, P. P., Majumder, S., Zoomers, A., & van Laerhoven, F. (2019). Factor Affecting Consumption of Water from a Newly Introduced Safe Drinking Water System: The Case of Managed Aquifer Recharge (MAR) Systems in Bangladesh. *Water*, *11*(12), 2459.	***Theory/Framework:*** This article leans on the RANAS framework that looks at risk, attitudinal, normative, ability, and self-regulation factors to predict households' propensity to adopt an innovation. ***Study sites***: 15 communities, in 7 sub-districts, in 3 districts ***Research methods***: Household surveys (N=780) and expert interviews (3), for data collection. Linear regression for the analysis	• Rather than committing exclusively to one drinking water option, households in Bangladesh often use a portfolio of sources that, in varying ways, to varying extents satisfy one or more out of several preferences they hold with regard to their drinking water. We found that perceived risk, costs, taste, self-efficacy, and form and intensity of competition with alternative drinking water options matter significantly in predicting the propensity of a household to accept a newly introduced drinking water option (e.g. MAR).	• **Do not target full and exclusive acceptance** of the drinking water option that you are advocating for. Households may use a portfolio of drinking water sources. • Assess the number and nature of **drinking water solutions that are already available** • Carefully **evaluate community preferences and perceptions** • Create new or tap into existing **local participatory capacities** to align what you offer with these demands. Focus on **hardware** (i.e. physical infrastructure), and on ***software* activities** (i.e. people's behavior)

Hasan, M.B., Driessen, P., Zoomers, A., Majumder, S., van Laerhoven, F. (resubmission awaiting). A community management plus model for the governance of rural drinking water systems: A comparative case study of Pond Sand Filter (PSF) systems in Bangladesh. *International Journal of the Commons*	**Theory/Framework:** This article combines insights gained from theory on institutions for collective action in the context of shared resource systems. We develop a set of requirements presumed necessary for collective action among resource users, and for collaboration between resource users and public agencies **Study sites:** 30 communities in 3 sub-districts, in 3 districts **Research methods:** 30 group interviews (8-12 participants per interview) with resource users, and 6 semi-structured interviews with public agents for data collection. Correlation significance tests for the analysis.	• A large group size, interdependency among the group members, heterogeneity of endowments, a high level of dependence on resource system, locally devised access and management rules and well-working collaboration between PSF users and the public agency are significantly associated with the occurrence of collective action among PSF users. • The latter (i.e. collaboration between PSF users and the public agency) is helped by transparency and inclusive decision-making procedures, but mostly by a relation that is characterized by trust.	• Attempts should be made to set **boundary rules** that determine who can use the system. • Form **user groups that are large enough** to achieve economies of scale • Form groups with members that **collaborated for other types of purposes, before**. • Make sure that your attempt to introduce a new and improved drinking water system is **demand rather than supply driven.** • **Involve the users** in the crafting of all rules regarding its governance • Guarantee the **support from a public agency.** • Invest in a **creating trust** between users and public agencies, and in **transparency** with regard to the making and enforcing of rules.
Hasan, M. B., Driessen, P., Zoomers, A., & Van Laerhoven, F. (2020). How can NGOs support collective action among the users of rural drinking water systems? A case study of Managed Aquifer Recharge (MAR) systems in Bangladesh. *World Development*, *126*, 104710.	***Theory/Framework***: This article combines insights gained from theory on institutions for collective action in the context of shared resource systems. We develop a set of requirements presumed necessary for guaranteeing both day-to-day and long-term collective action among local shared DWS users ***Study sites:*** 11 MAR sites in 10 communities (Union Parishads), in 8 sub-districts (Upazila) in 3 districts. ***Research methods***: Semi-structured interviews with 110 representatives of MAR users, and representatives of 7 NGOs for data collection. Qualitative methods for the analysis.	• NGO-supplied drinking water infrastructure projects routinely include collective action development approaches. • However, NGO support impact on community management of drinking water systems seems minimal. • NGO support is not driven by a vision regarding collective action requirements. • If targeting collective action requirements, NGO support imposes generic approaches. • NGO support to empower communities to craft self-management solutions is lacking.	• **Prioritize the support of collective action** among the users of shared resource systems over more conventional forms of support that focus on the transfer of capacities and resources • **Experiment with different approaches** and activities, and **monitor and evaluate** the outcomes thereof to **learn what works** • Focus on **community empowerment**, and **allowing users to craft their own ways** of meeting the requirements for successful and durable forms of collective action • **Do not provide NGOs with rigid instructions** based on predefined problem definitions.

OUTPUT RELATED WITH SITE SELECTION			
Naus, F. L., Schot, P. P., Ahmed, K., & Griffioen, J. (2019). Groundwater salinity variation in Upazila Assasuni (southwestern Bangladesh), as steered by surface clay layer thickness, relative elevation and present-day land use. *Hydrology and Earth System Sciences*, *23*(3), 1431-1451.	Our approach involved three steps: • a geological reconstruction, based on the literature; • fieldwork to collect high-density hydrological and lithological data; and • data processing to link the collected data to the geological reconstruction in order to infer the evolution of the groundwater salinity in the study area.	Groundwater salinity variation is controlled by both paleo and present-day hydrogeological conditions, depending on the thickness of the surface clay layer.	• Pay attention to our results regarding **how salinity variation in southwestern Bangladesh was formed** when considering the location of MAR or other drinking water systems. See article for more details.
Naus, F. L., Schot, P., Ahmed, K. M., & Griffioen, J. (2019). Influence of landscape features on the large variation of shallow groundwater salinity in southwestern Bangladesh. *Journal of Hydrology X*, *5*, 100043.	• We aimed to assess the regional shallow (<60 m) groundwater salinity variation with a higher resolution as a function of landscape features and associated hydrological processes. • Spatial variation in groundwater salinity was assessed using 442 EC measurements from previous studies and 1998 new EC measurements. • Groundwater EC values were correlated with well location data (latitude, longitude and depth of the filter) and landscape feature data (elevation, soil type, land use and surface clay thickness). • Additionally, we performed a geomorphological analysis of landscape features to infer associated hydrological processes.	This study is the first to demonstrate the relation between landscape features, hydrological processes and regional groundwater salinity throughout southwestern Bangladesh. • We interpret wide fluvial zones to be remnants of sandy deposits in large paleo channels which allow freshwater recharge, resulting in groundwater that is mostly (75%) fresh. • Narrow fluvial zones, tidal fluvial zones, and fluvial zones next to tidal rivers are more susceptible to lateral saline water flow or saline water recharge by occasional tidal flooding, and only contain some shallow fresh groundwater in high-lying zones. • Tidal flat or tidal fringe zones hardly contain any fresh groundwater.	• Pay attention to our **guidelines regarding how salinity occurrence can be established based on landscape features and hydrological process** when considering the location of MAR or other drinking water systems. These guidelines are specified in the discussion section of the article in (much) more detail.
Naus, F. L., Burer, K., van Laerhoven, F., Griffioen, J., Ahmed, K. M., & Schot, P. (2020). Why do people remain attached to unsafe drinking water options? Quantitative evidence from	This study aims to determine why and to what extent people remain attached to unsafe water options. Through 262 surveys, this study explores whether five explanatory factors (risk, attitude, norms, reliability, and habit) pose barriers to switching from unsafe to safe	• Users' attachment to using pond water is generally low • Users are more attached to shallow tube wells • The safe alternatives score significantly better than pond water and are estimated	• In order to wean households off pond water, and have them switching to (e.g.) MAR, it is recommended to focus awareness raising campaigns on the **risk and inconvenience of drinking pond water**.

Southwestern Bangladesh. *Water*, *12*(2), 342.	drinking water options or whether they could act as facilitators of such a switch.	to have the potential to be adopted by pond water users. • Deep tube well, rainwater harvesting, and pond sand filter also score better than shallow tube wells and could also have the potential to replace them.	• The largest potential for getting shallow tube well users to adopt alternative, safe options is to focus on the **risk associated with drinking groundwater with elevated levels of arsenic or salinity**.
Naus, F.L., Schot, P., van Breukelen, B.M., Ahmed, K.M, Griffioen, J. (to be submitted soon). Potential for Managed Aquifer Recharge in southwestern Bangladesh based on social necessity and technical suitability	• We determined potential for MAR throughout the region by combining assessments of its necessity and the technical suitability for MAR. • The assessment was based on the largest groundwater quality dataset compiled to date in southwestern Bangladesh (Khulna, Satkhira and Bagerhat districts), which contains 3716 salinity measurements and 827 arsenic measurements. • We determined the impact of density-driven flow on fresh recovery efficiency by the MAR systems in brackish groundwater environments and assessed the vulnerability of recovered water to mixing with the native brackish-saline or arsenic-contaminated groundwater.	The results determine where the potential of MAR is limited due to • frequent inundations (e.g. floodplains) • low demand (e.g. the presence of good quality groundwater) The results subsequently establish where the potential for MAR is high, due to: • a combination of technical suitability and high demand (e.g. the absence of water free of salinity and arsenic) Furthermore, we determine where there is a need for MAR (i.e. due to saline groundwater people turn to unsafe pond water), but where due to groundwater salinity MAR design needs to consider a higher infiltration rate to limit impacts of density-driven flow and MAR water quality deterioration.	Use the outcomes of this research for the selection of (MAR) sites to: • (i) **avoid** the areas with low potential due to technical **unsuitability and low demand** that we identify, • (ii) **focus** on the areas with **high suitability and high demand** for a delivery system like MAR. • (iii) consider areas with high demand and sub-optimal suitability, and **invest in systems designs that limit the impact of groundwater salinity**