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Technical Note 5

Feasibility of Managed Aquifer Recharge in the Barind

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Feasibility of Managed Aquifer Recharge in the Barind region in Bangladesh

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SUMMARY AND CONCLUSIONS

Over extraction of groundwater in the Barind region in Bangladesh is not sustainable and undesired consequences are visible. Managed Aquifer Recharge (MAR), the active replenishment of groundwater, has been mentioned as a solution to counter the ongoing depletion. This study investigates the groundwater system of the high Barind, the water balance, and discusses potential MAR designs that could work in this challenging setting.

To determine the sustainability of the developed groundwater system, it is important to know the terms of the water balance and the groundwater system. The groundwater system clearly shows declining groundwater tables below the high Barind, and recovering groundwater levels near the Rivers surrounding the Barind. This indicates that it is important look at the different physiographic units when reporting numbers, and not Upazilla wise. A scan of literature on the water balance of the area shows widely varying numbers, possibly partly because they are often reported per Upazilla. For this reason, no good assessment of the groundwater depletion and the sustainability of the groundwater system could be made. Therefore, for further analysis, the water balance from the Meta-model was used.

For the challenging setting in the high Barind with a thick clay layer at the surface, three MAR designs were discussed. 1) The original design reported in literature that consists of a recharge shaft in the irrigation canals, 2) a design consisting of a pond connected to the irrigation canal from which water can be pumped through a separate coarse sand filter that feeds 10 injection wells, and 3) rooftop rainwater harvesting. It is found that the original design (1) shows progressive clogging over time which results in poor performance over time. Design 2 avoids this clogging by having a standalone coarse sand filter which can be maintained, and by using wells that can be flushed. The rooftop rainwater harvesting design (3) can only be used with large enough roofs, and only small volumes can be recharged.

The suitability maps of MAR in the Barind show that recharge through infiltration wells penetrating the low conductivity clay layer seems to be the best way for artificial recharge.

The feasibility study shows that, even though the original recharge wells in the irrigation canal (design 1) are relatively cheap, the costs over time are higher than the more expensive design with a pond and a coarse sand filter next to the irrigation canal (design 2). The reason is that design 2 is expected to show better performance over time. Design 3 is relatively expensive when looking at price per recharged volume. However, it should be realised that rooftop rainwater harvesting can lead to a sustainable source of fresh water for small communities that currently don't have such a source, partly due to the groundwater depletion caused by irrigation. In summary, rooftop rainwater harvesting should not be seen as a way to partially restore the water balance, but as a way to resolve the undesired consequences of over depletion for small communities.

Our recommendations are to focus on improving the understanding of the groundwater system and the water balance. Only then the unsustainability of the developed groundwater system can be accurately quantified, which is key to determine the volume of artificially recharged groundwater needed to push the system towards a more sustainable state. Improved understanding of the water balance and the groundwater system also allows for the construction of a meaningful groundwater model which can inform the sustainability assessment. The water balance should not be determined upazilla-wise, but per physiographic unit. For the MAR designs, a closer look at the cost estimates and materials may result in lower cost estimates and more cost-effective designs. For design 2, it would be interesting to see if they can be placed next to groundwater extraction wells.

This study provides an estimate of the costs involved for MAR in the Barind to move to a more sustainable water balance. The costs reported in this study should be compared to other IWRM measures to decide on the most effective set of measures.

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ACRONYMS AND ABBREVIATIONS

BDT– Bangladesh Taka

BMDA– Barind Multipurpose Development Board

BMDP– Barind Multipurpose Development Project

BWDB– Bangladesh Water Development Board

CEGIS– Center for Environment and Geographic Information Service

CSIRO– Commonwealth Scientific & Industrial Research Organisation

DEM– Digital Elevation Model

DPHE– Department of Public Health Engineering

DTW–Deep Tube Well

ET– Evapotranspiration

GIS– Global Information System

IWM– Institute of Water Modelling

JCP– Joint Corporation Programme

MAR– Managed Aquifer Recharge

MSL– Mean Sea Level

NGO– Non-Government Organization

NIR– Net Irrigation Requirement

NTU– Nephelometric Turbidity Unit

PE– Polyethylene

PVC– Polyvinyl Chloride

RE– Recovery Efficiency

RW– Recharge Well

RWH– Rain Water Harvesting

STW– Shallow Tube Well

UNDP– United Nation Development Programme

UNICEF– United Nation International Children Emergency Fund

ΔD– Change in Discharge

ΔR– Change in Recharge

ΔV– Change in Volume

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1 INTRODUCTION

During the last decades, the Barind region in northwestern Bangladesh has developed from an area with low agricultural productivity in the early 1980's to an important agricultural region vital to Bangladesh food supply. The success behind this transformation in this drought-prone area is dry season irrigation using groundwater from deep tube wells. However, recharge of groundwater during the wet season in this area is limited due to the low infiltration capacity of the thick clay layer at the surface (e.g. Adhem et al., 2010; Jahan et al., 2010a, b; Figure 1). As a result, groundwater levels in the region are declining rapidly (e.g. Rahman et al., 2016) and groundwater resources in some areas are already inadequate to meet the present water demand (Banerjee and deSilva, 2020). This is an unsustainable situation, and if continued, it will affect not only the food production capacity, but also impact domestic water availability. In addition, it is expected that other groundwater dependent functions are or will be affected, such as base flow or groundwater dependent nature.

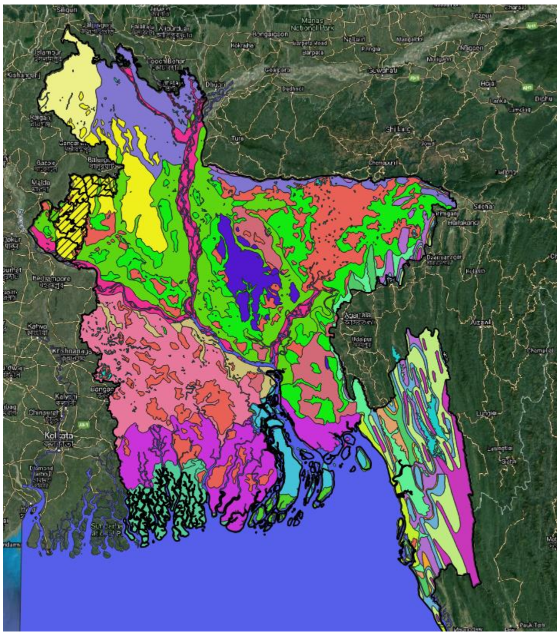


Figure 1 Geological map of Bangladesh with the Barind tracts in yellow and the targeted upazillas in the High Barind hatched.

Managed Aquifer recharge (MAR) has been mentioned as a solution for the groundwater depletion (e.g. Hossain et al. 2021). MAR is defined as the purposeful recharge of water to aquifers for subsequent recovery or for environmental benefit (Dillon et al., 2009). MAR may be used to replenish depleted aquifers, in association with demand management strategies to bring aquifers back into hydrologic equilibrium while minimizing adverse impacts on livelihoods of irrigation communities. MAR can consist of a multitude of techniques, from infiltration ponds, changes in land use to recharge wells. The suitability for MAR is dependent on the geological and climatological setting, and so is the type of technique that could work. Also factors such as agricultural and municipal water demand and source water availability and quality are important. In this study we only assess the water quantity, and not the water quality.

The feasibility of MAR depends on the costs of applying MAR and benefits it brings. For the Barind, the feasibility of MAR in the Barind has not yet been established. The objective of this study is to assess the feasibility of MAR in the Barind. For this purpose, we bring together the following information:

- An analysis of the groundwater system
- An assessment of the different water balance terms
- Designs of MAR installations and their potential yield
- Assessment of the suitability of MAR

- Assessment of feasibility of MAR

If MAR is considered to be feasible, the results of this report can be used to request funding for MAR installations by the Barind Multipurpose Development Board (BMDA).

Study Area

The Barind region belongs to one of the driest regions of Bangladesh (Jahan et al., 2010). The area has a subtropical monsoon climate characterized by three distinct seasons: 1) the dry winter season from November to February, 2) the pre-monsoon hot summer season from March to May, and 3) the rainy monsoon season which lasts from June to October (Jahan et al., 2010; Shahid & Hazarika, 2010). Mean annual rainfall varies between 1310 and 1625 mm.

The Barind tracts consist of elevated Pleistocene terraces. The subsurface of these terraces is characterized by a thick clay layer (>30 m) at the top overlying a 10 to 20 m thick sand layer. This sand layer forms the aquifer that sources the groundwater used for irrigation. The westernmost Barind tract is called the high Barind, which reaches elevations higher than 50 m (Figure 2). This high Barind tract is the subject of our study, and therefore we are targeting the following upazillas: Godagari, Tanore, Nachol, Niamatpur, Gomastapur, Porsha, Sapahar, Patnitala, Dharmoirhat. The elevated terraces have been incised by several Rivers, which have often deposited floodplain clays on the Barind clays. Most notable are the Padma (Ganges) in the south, the Mahananda River in the west, and the Atrai River in the east. During the inception of this project, a field visit was made including a debrief report (**Error! Reference source not found.**).

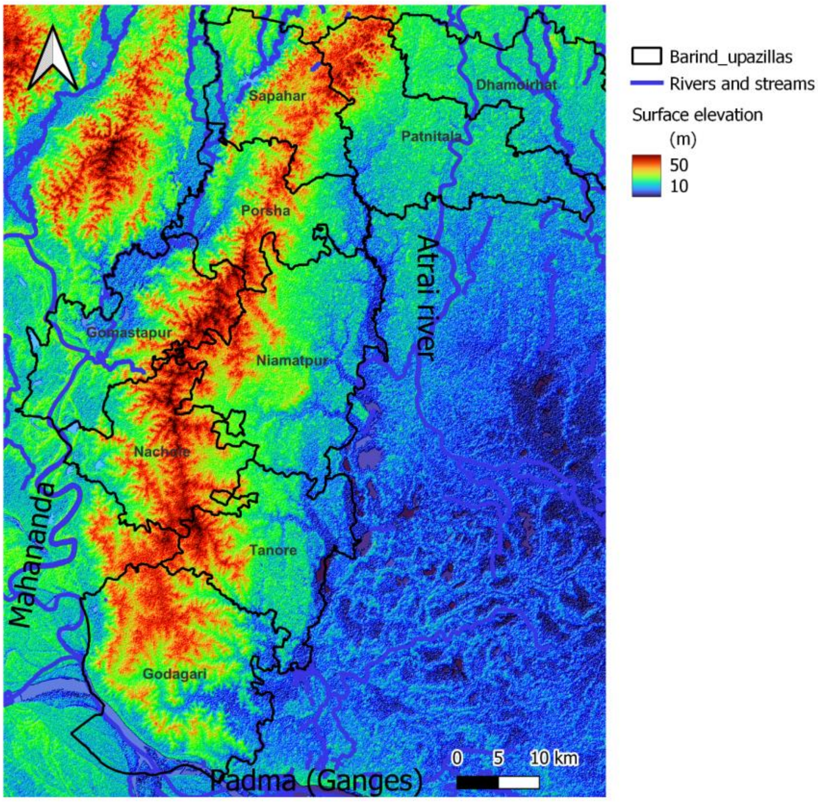


Figure 2 Digital elevation model of the high Barind and the upazillas targeted in this study. The high Barind is bounded in the west by the Mahananda River, in the east by the Atrai River and in the south by the Padma River.

2 GROUNDWATER SYSTEM AND WATER BALANCE

2.1 Water balance and sustainable groundwater development

To assess the suitability of Managed Aquifer Recharge, it is important to understand how the groundwater system works in the "natural" state and in the developed state, and what sustainable groundwater development may look like.

2.1.1 Background sustainable groundwater management

A groundwater system prior to development is in a dynamic balance, which means that recharge of groundwater is in balance to the water leaving the system as discharge (Figure 3a; Konikow and Bredehoeft, 2020).

When wells are placed and the system becomes developed, it introduces new discharge to the system. This water is balanced from three potential sources: 1. an increase in the recharge to the aquifer, 2) a decrease in groundwater discharge or 3) a reduction in groundwater storage (Figure 3b; Konikow and Bredehoeft, 2020). Hence, any groundwater pumping must be balanced or compensated by changes in the other terms of the water budget. The change in Recharge (Δ R) or Discharge (Δ D) is called *capture* by the well that would otherwise not have entered the groundwater system or otherwise would have discharged from the groundwater system naturally. A negative change in the volume of groundwater in storage (Δ V) represents a depletion of the volume of groundwater stored in the aquifer.

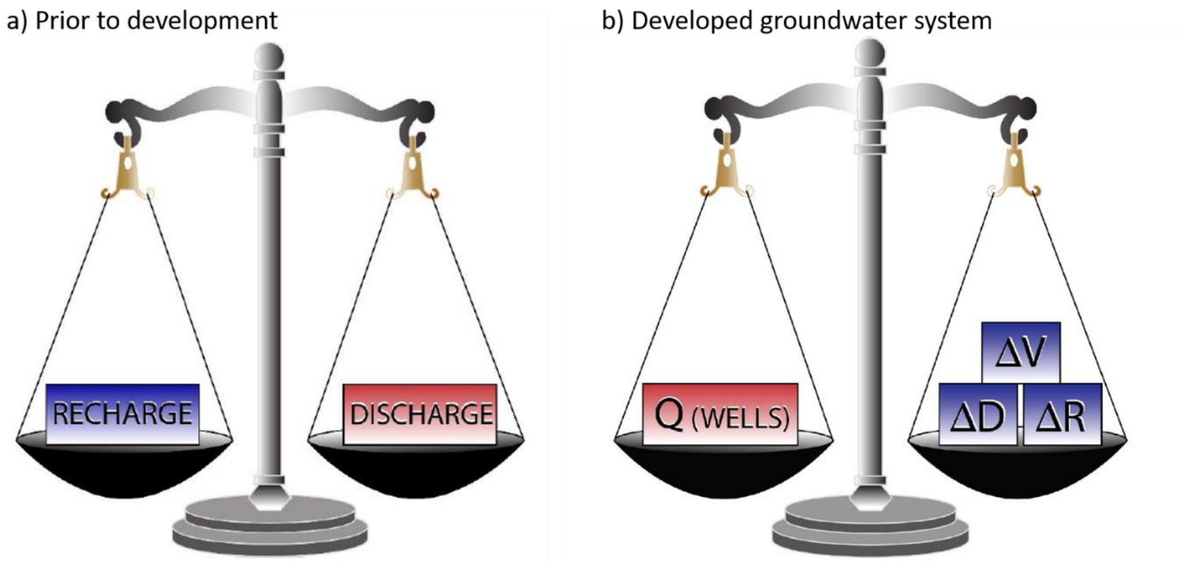


Figure 3 Schematic illustration of the groundwater balance before and after development

a) The natural groundwater balance with a dynamic equilibrium between recharge and discharge, and b) the developed groundwater balance required to offset a new pumping stress in the aquifer. ΔV is the change in storage, ΔD the change in groundwater discharge, and ΔR is the change in recharge (from (Konikow and Bredehoeft, 2020).

Long-term development of the groundwater system aims to maintain sustainable pumping indefinitely. This means that eventually storage is no longer being depleted and pumping is balanced by capture (Figure 4). Hence, to determine if a developed groundwater system is sustainable (or can be made sustainable using additional recharge), it is important to know:

- What are the changes in recharge and discharge brought on by the pumping?
- Can the system reach a new equilibrium in which storage is no longer being depleted?
- How long will it take to reach the new equilibrium?
- If a new equilibrium cannot be achieved, for how long can the pumping be maintained?
- Is the capture and change in storage acceptable from a water and environmental policy and management perspective?

The latter question if the capture and change in storage of the groundwater system is acceptable from a water and environmental policy and management perspective perhaps the most important. It should be realized that any extraction of groundwater is accompanied by reduced discharge of groundwater. Unsustainable extraction of groundwater during the dry season could lead to streamflow depletion. This could even lead to drying up of streams, and could hamper other functions of the streams, such as supporting nature, fisheries, or domestic water supply.

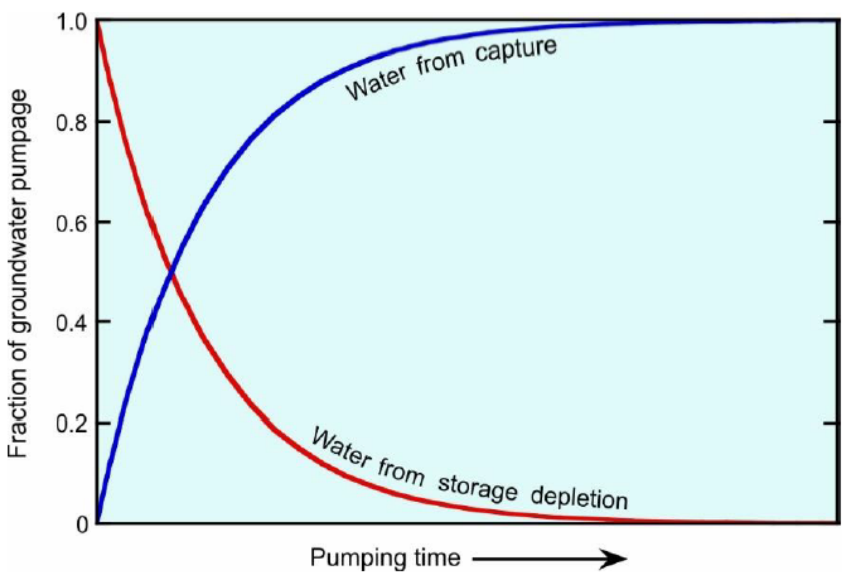


Figure 4 Change in water source of a well with time. At t=0 the source is primarily storage depletion. With time, capture through reduced discharge or increased recharge takes over (From Konikow and Bredehoeft, 2020).

As already indicated, MAR may be used to replenish depleted aquifers to bring aquifers back into hydrologic equilibrium while minimizing adverse impacts on livelihoods of irrigation communities. Often, this will be in combination with other measures, such as demand management (e.g. more efficient irrigation, crop change) and tapping alternative supplies for groundwater (e.g. surface water irrigation). The preferred final situation would be a groundwater use without excessive adverse impacts, as illustrated in Figure 5.

Groundwater modelling could be a useful tool to answer the questions of whether the developed groundwater system is sustainable and assess adverse impacts and potential measures. However, for the construction of an informative and useful groundwater model, the groundwater system must be well understood and monitored. In this study we bring together essential information to do so.

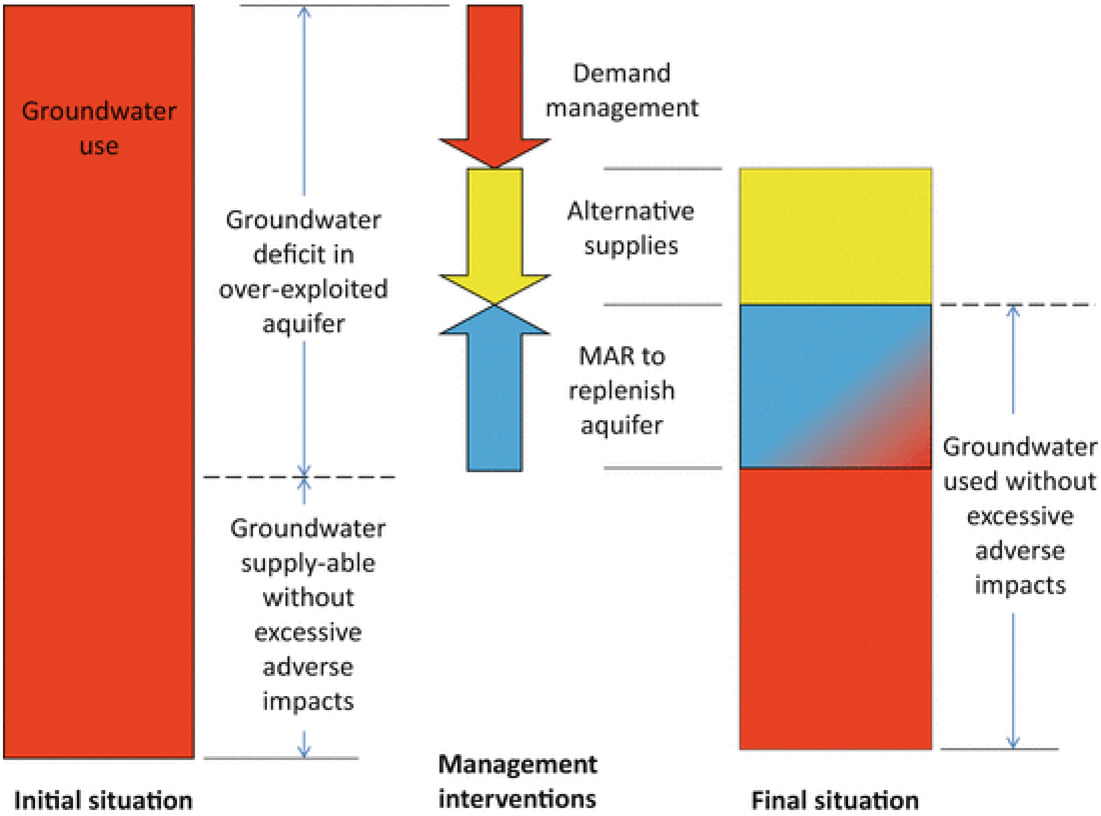


Figure 5 An aquifer can be brought into hydrologic equilibrium by either reducing extraction, or augmenting supplies, either through groundwater replenishment or providing alternative supplies (conjunctive use) (From Dillon et al. 2012)

2.1.2 Groundwater system of the high Barind

The Barind area receives an annual rainfall of about 1600 mm (e.g. Jahan et al., 2010b), which makes it one of the driest regions in Bangladesh. This rain falls mainly during the monsoon, from April to September. During the monsoon, most water will be captured in rice paddies, canals and ponds, and the remaining water will leave the area as runoff, since the infiltration capacity of the thick clay is low. However, a small portion of the precipitation will infiltrate and thereby recharge the groundwater. This will lead to higher groundwater heads below the higher elevated areas, and a groundwater gradient to the surrounding Rivers. Along and in these Rivers, the groundwater will be discharged as seepage. This groundwater discharge is important as it delivers a continuous supply of water to the Rivers, also during the dry period; the base flow. Often, this base flow delivers important functions, such as water for shipping, fisheries, nature and domestic water supply.

The subsurface of the Barind consists of a thick clay layer, that can reach a thickness of over 50m (Hasan et al., 2016; Figure 6). It overlies a sand layer, often indicated as the first aquifer, which can reach a thickness of 30 m (Hasan et al., 2016). The sand layer is coarse at the bottom, and fine at the top. In this study we treat the aquifer as one system. However, it should be noted that the aquifer formed by the composite sand layers is complex, contains clay layers, and is even described as a multi-aquifer system (Rushton et al., 2020). At the bottom the aquifer is bounded by a black plastic clay (Hasan et al., 2016).

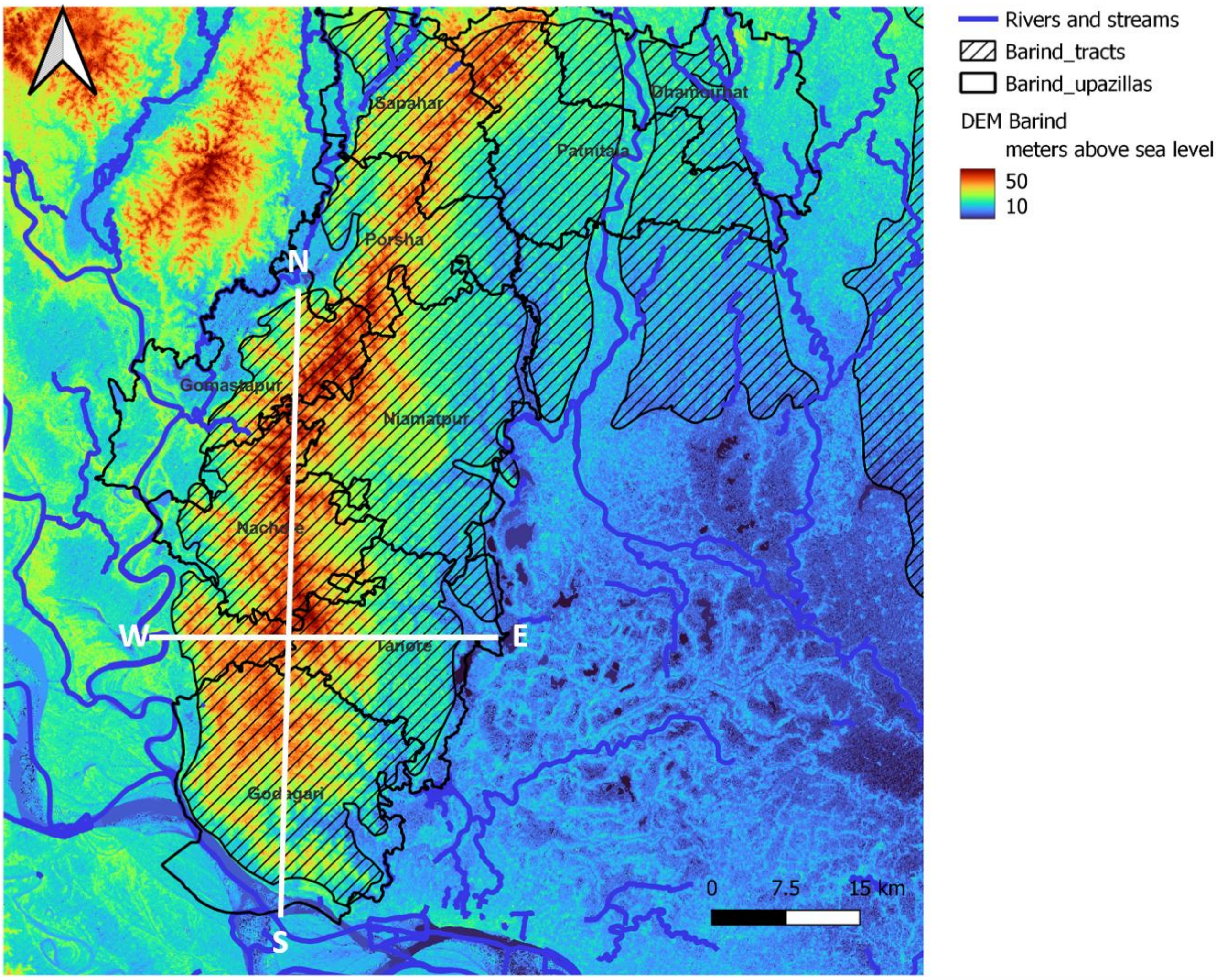


Figure 6 Location of the Barind tracts in the northwest of Bangladesh, the upazillas involved plotted on top of a digital elevation model (DEM) of the area derived from SRTM data. The white lines indicate the locations of the cross sections used for the conceptual models in Figure 7and Figure 8.

In the natural groundwater system of the Barind prior to development, recharge and discharge were in dynamic balance. Recharge mostly took place during the monsoon, while discharge into streams and to the surrounding Rivers probably took place all year. This means that groundwater discharge may be important for the ecosystems and other functions in and around the Rivers surrounding the Barind (Figure 7). The direction and distribution of the discharge will be dependent on the hydraulic resistance of the beds of the surrounding Rivers. In other words, it is dependent whether a layer of clay separates the River bed sands and the aquifer, or if the sands are hydraulically connected. It is quite certain that the sandy channel belt deposits of the Padma are hydraulically connected to the first aquifer (e.g. IWM, 2006). For the Mahananda and Atrai Rivers, to our knowledge this has not been established yet, although it is suggested that the Barind clay underlies the channel belt deposits (e.g. Rashid et al., 2015).

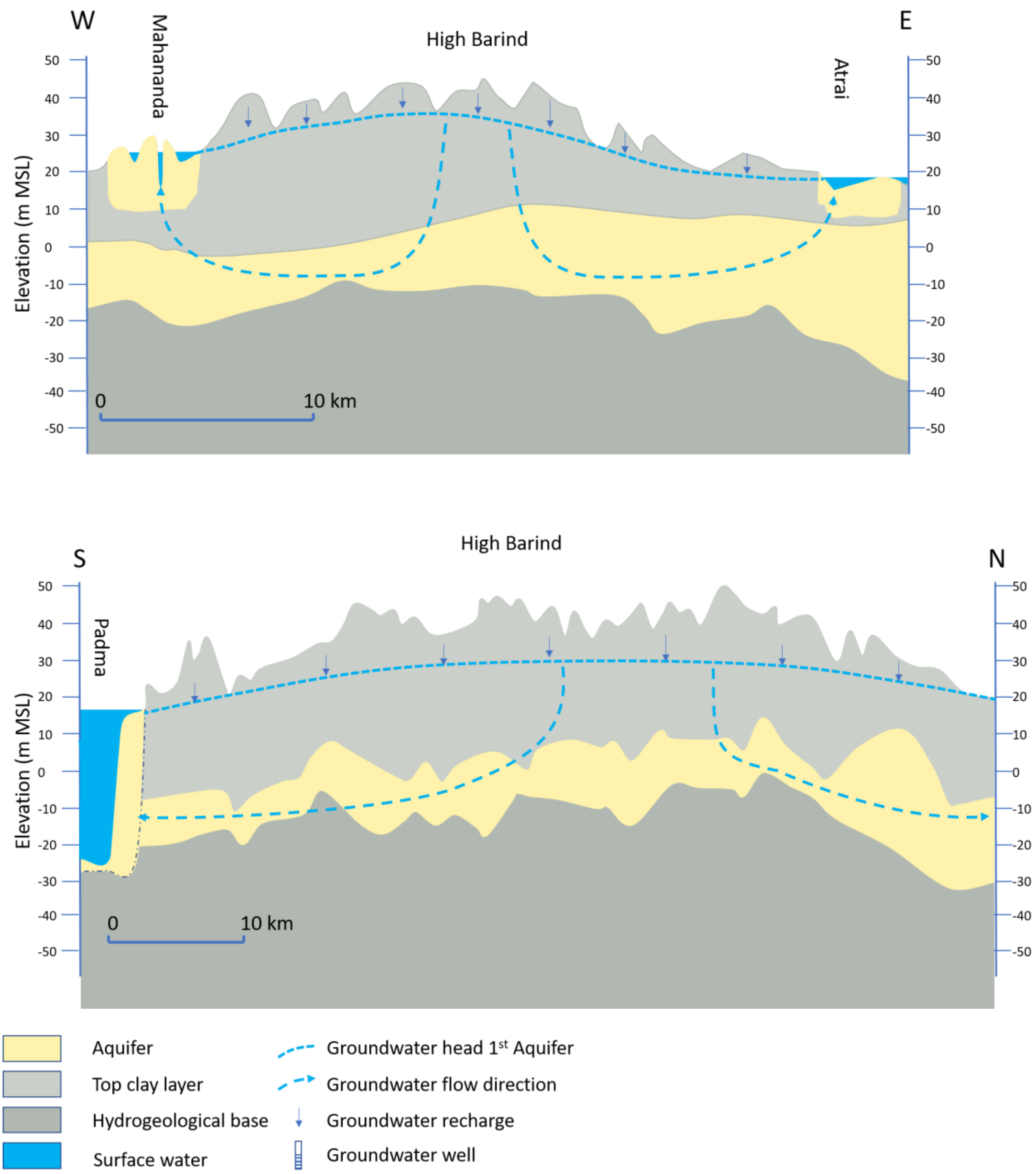


Figure 7 Conceptual cross sections of the natural groundwater system of the high Barind during the monsoon; Upper panel shows a west – east cross-section, the lower panel a south – north cross section. Configuration of confining clay layer, aquifer and hydrogeological base is loosely based on cross sections from literature (Hasan et al., 2016)

2.2 Developed groundwater system

In the developed state (Figure 8), in several areas, a continuous decline of the groundwater levels in monitoring wells suggests that no equilibrium has been reached and that storage is still being depleted.

The drawdown by groundwater wells will create a gradient that captures the recharge surrounding the wells. This captured recharge by pumping will not reach the discharge areas. When the pumping continues, the drawdown will eventually result in groundwater heads lower than the River level, which induces recharge from the Rivers into the aquifers. Hence, the discharge from wells is balanced by recharge from Rivers. This may already be the case in the groundwater wells near the Rivers. Also, in the natural system, increasing River levels during the monsoon period will results in recharge near the Rivers. In the developed system this recharge will reach further "upstream" in the groundwater system and may also take place during the dry season.

It is an important notion that the groundwater system in the high Barind may reach a equilibrium situation in the future due to recharge from surrounding Rivers, and locally this is possibly already the case. However, it also has implications for groundwater quality, when polluted River water is drawn into the aquifer. In addition, even though the situation is "sustainable" is a sense that it is in balance and can be continued for a prolonged period of time, it doesn't mean that it doesn't have any negative consequences. The negative consequences could be deterioration of discharge dependent ecosystems, diminished baseflow in Rivers ("streamflow depletion"), or lack of groundwater accessibility for rural communities due to lower groundwater tables.

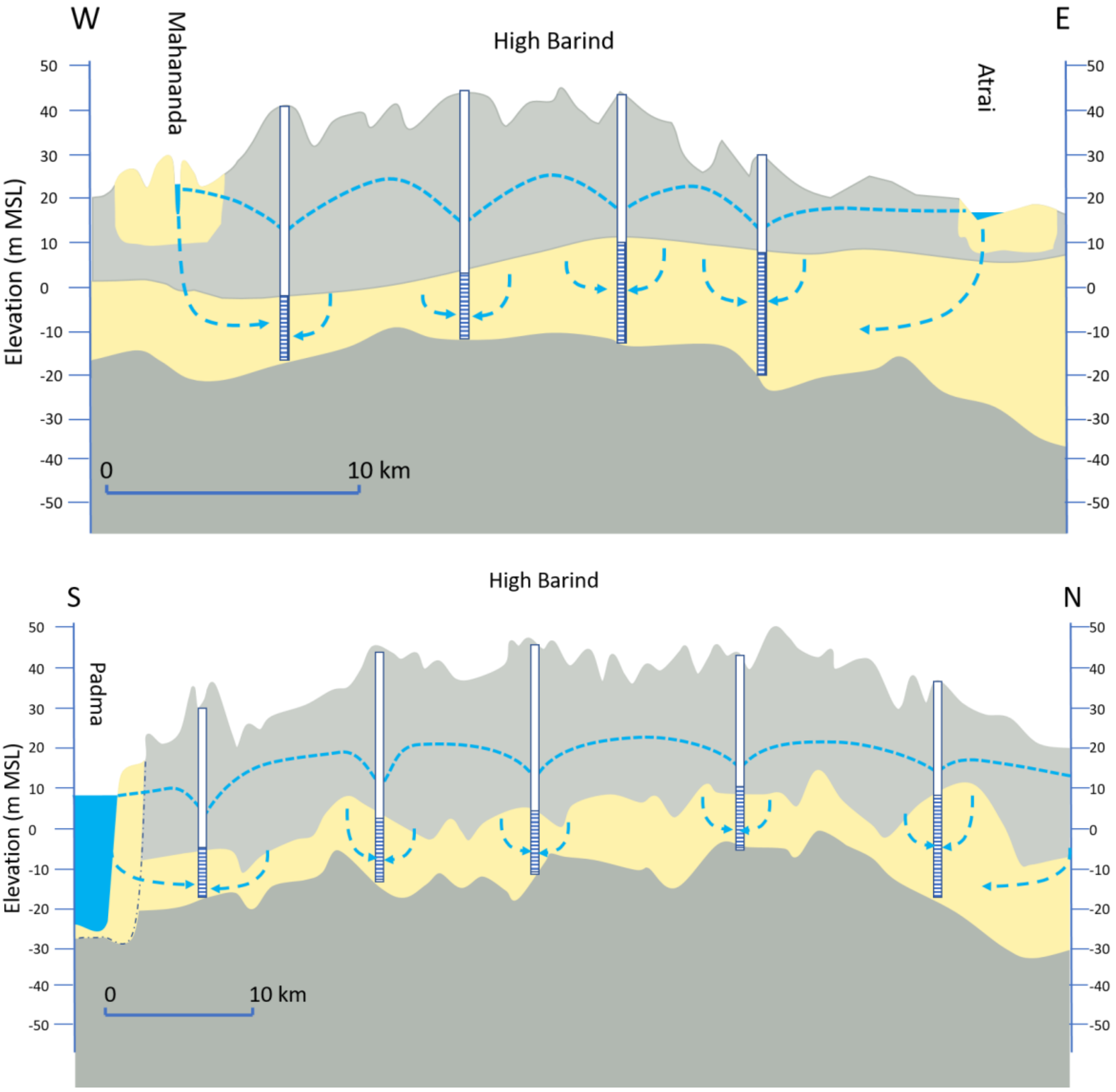


Figure 8 Conceptual drawing of the developed groundwater system of the high Barind during the dry period. ; Upper panel shows a west – east cross-section, the lower panel a south – north cross section. Configuration of confining clay layer, aquifer and hydrogeological base is loosely based on cross sections from literature (Hasan et al., 2016). The legend of the units is provided in Figure 7.

3 OBSERVED TRENDS IN GROUNDWATER

To assess the trends in groundwater, time series from groundwater monitoring wells from the Bangladesh Water Development Board (BWDB) was collected for all the 9 Upazilas. The considered period ranged from 2010 to 2021 since for this period consistent high-resolution data is available. The data-set was checked on quality and consistency and the hydraulic trend for all the individual tube wells was drawn. To understand the variation of groundwater levels, spatial distribution maps of groundwater levels for the different times have been prepared.

It should be noted that in the year 2010 excessive groundwater use had been going on for almost 30 years already. Therefore, the groundwater levels from 2010 should not be confused with pre-development groundwater data. Unfortunately, no trustworthy time series of ground water levels could be found that covers the entire period from the early stages of development of the Barind to the present.

3.1 Analysis of groundwater level hydrographs

To assess the yearly dynamics in groundwater level and long-term trends, hydrographs were generated for different stations. Figure 9 shows a number of representative groundwater hydrographs. **Error! Reference source not found.** shows all the hydrographs including a description.

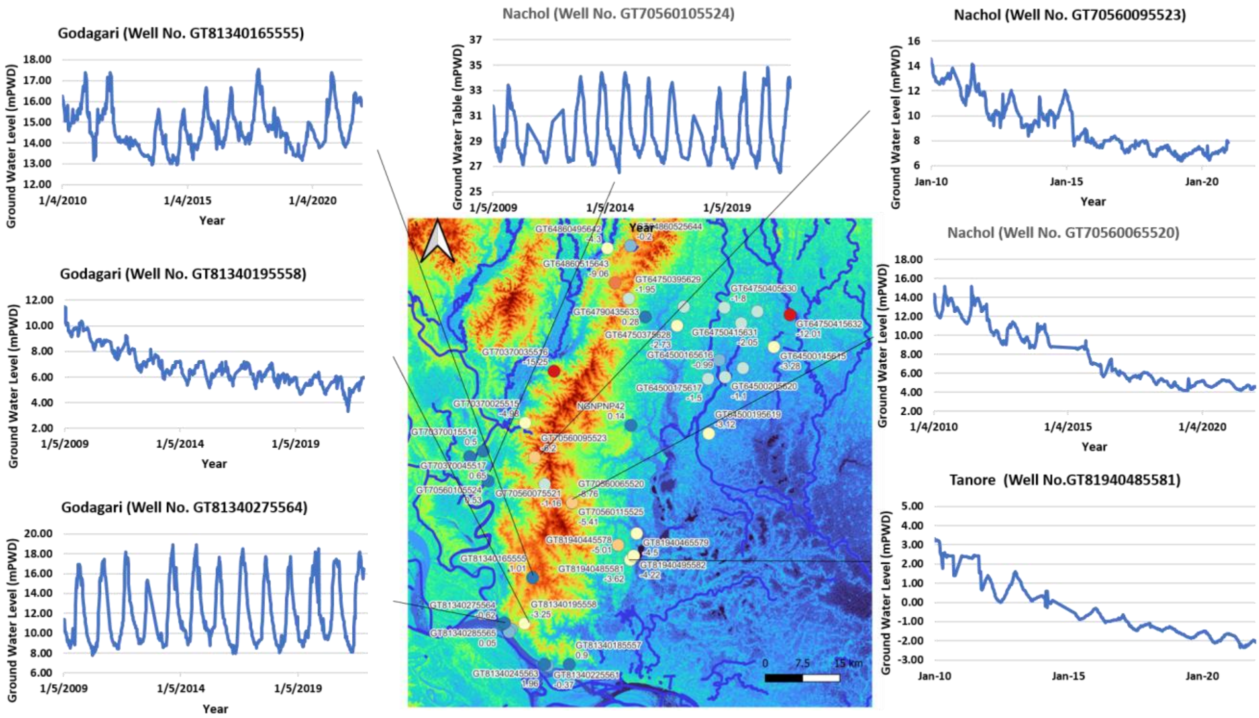


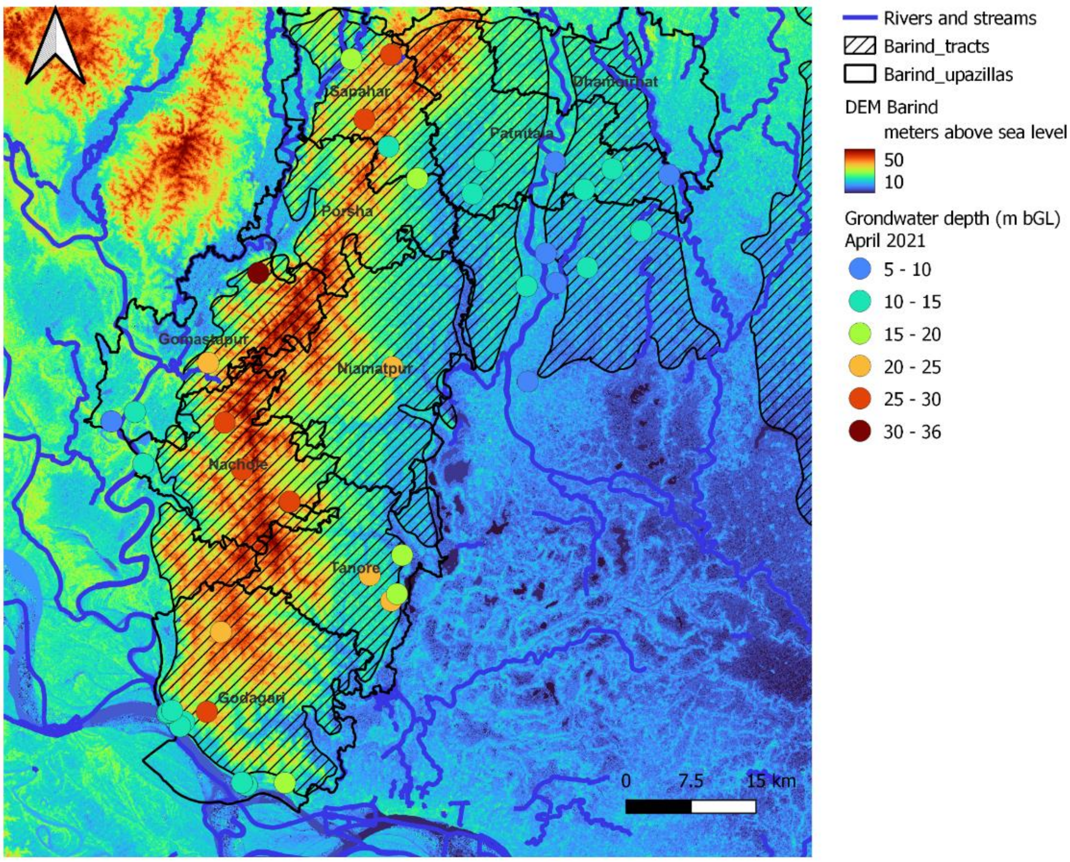
Figure 9: Selection of hydrographs from monitoring wells. Labels of the wells indicate the well identification number and groundwater levels in September 2021 compared to September 2010.

The plots show that the monitoring wells show very different dynamics. Some show a large seasonal variation and almost no long term trend, while others show a more gradual trend and only small seasonal dynamics. Some of the irregular time-series may be caused by poorly performing monitoring wells, for instance due to clogging. In addition, it cannot be ruled out that the monitoring wells are within the area of influence of deep tube wells.

In general, the plots show that near Rivers, the seasonal dynamics are high with up to 10 m variation between the dry season and the monsoon season (e.g. GT81340275564, GT70560105524). On the high Barind, most wells show some seasonality of a couple of meters between the dry and monsoon season (e.g. GT81340195558, GT70560095523, GT70560065520 and GT81940485581). In addition, these wells all show a declining trend of about half a meter per year in the monsoon season. This declining trend seems to gradually slow down. However, some wells on the Barind do not show a clear trend and no depletion is visible during the plotted period (e.g. GT81340165555).

3.1.1 Spatial distribution of groundwater depth

The spatial distribution of groundwater depths (Figure 10) shows that the groundwater is deepest in areas with higher elevation, such as on the high Barind. Along the Rivers the groundwater depth is closer to the surface. Below the high Barind, the groundwater table is over 25 m deep, both at the end of the dry season as the end of the monsoon season. Along the Rivers, after the dry season, the groundwater levels are within 15 m and mostly within 10 m from the surface. After the monsoon season, they are usually at least 5 m higher. Some outliers are present, which are expected to be the result of an erroneous recorded elevation of the groundwater well head.



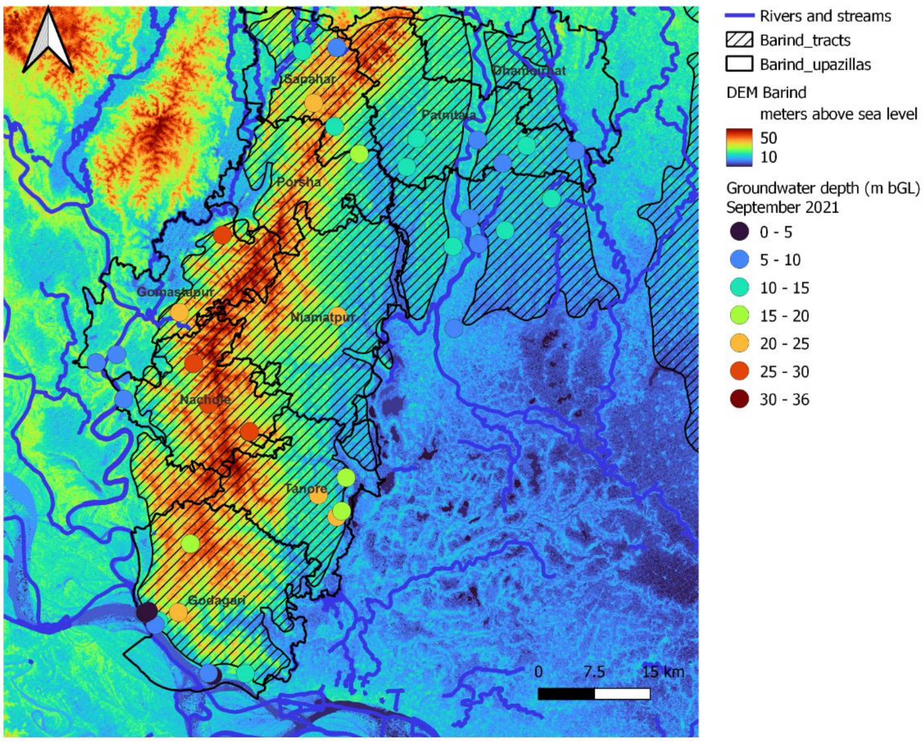


Figure 10 Spatial distribution of groundwater depths below ground level. Upper Panel is for April 2021 (end of dry season), lower Panel is for September 2021 (end of monsoon season).

3.1.2 Spatial distribution of groundwater elevation (hydraulic head)

The spatial distribution in groundwater elevation or hydraulic head (Figure 11) gives information about groundwater flow directions. Groundwater flows from higher hydraulic head to lower hydraulic head. The figures show that the monitoring wells in the west along the Mahananda River show the highest groundwater elevations of around 30 m above MSL. Below the ridge in the high Barind, the groundwater elevations are around 10 m above Mean Sea Level (MSL), whereas in the east they reach values between 5 and -5 m MSL. This trend is present in both the dry season and the monsoon season. Below the high Barind, the highest elevations are reached in well GT81340165555.

If the high groundwater levels along the Mahananda are indeed correct, the gradient implies that groundwater moves from the Mahananda region towards the east, below the Barind, and towards the Atrai River where it is discharged. It would also imply that all recharged groundwater from the Barind region will eventually discharge into the Atrai River. During the dry season, there seems to be a gradient from the high Barind towards the Padma in the south. During the monsoon season with high River levels, this trend is reversed, and Padma River infiltrates the aquifers.

The groundwater elevation in many places is near the bottom of the confining layer. In the east, the elevations are even below MSL. When the groundwater levels reach below the confining layer, an interesting situation exists in which a phreatic water table is formed in the aquifer. This has also been observed in the south near the Padma River. A result would be that pumping becomes easier, since the groundwater comes from phreatic storage instead of elastic storage. However, the groundwater system in the confining layer becomes decoupled from the groundwater system in the aquifer.

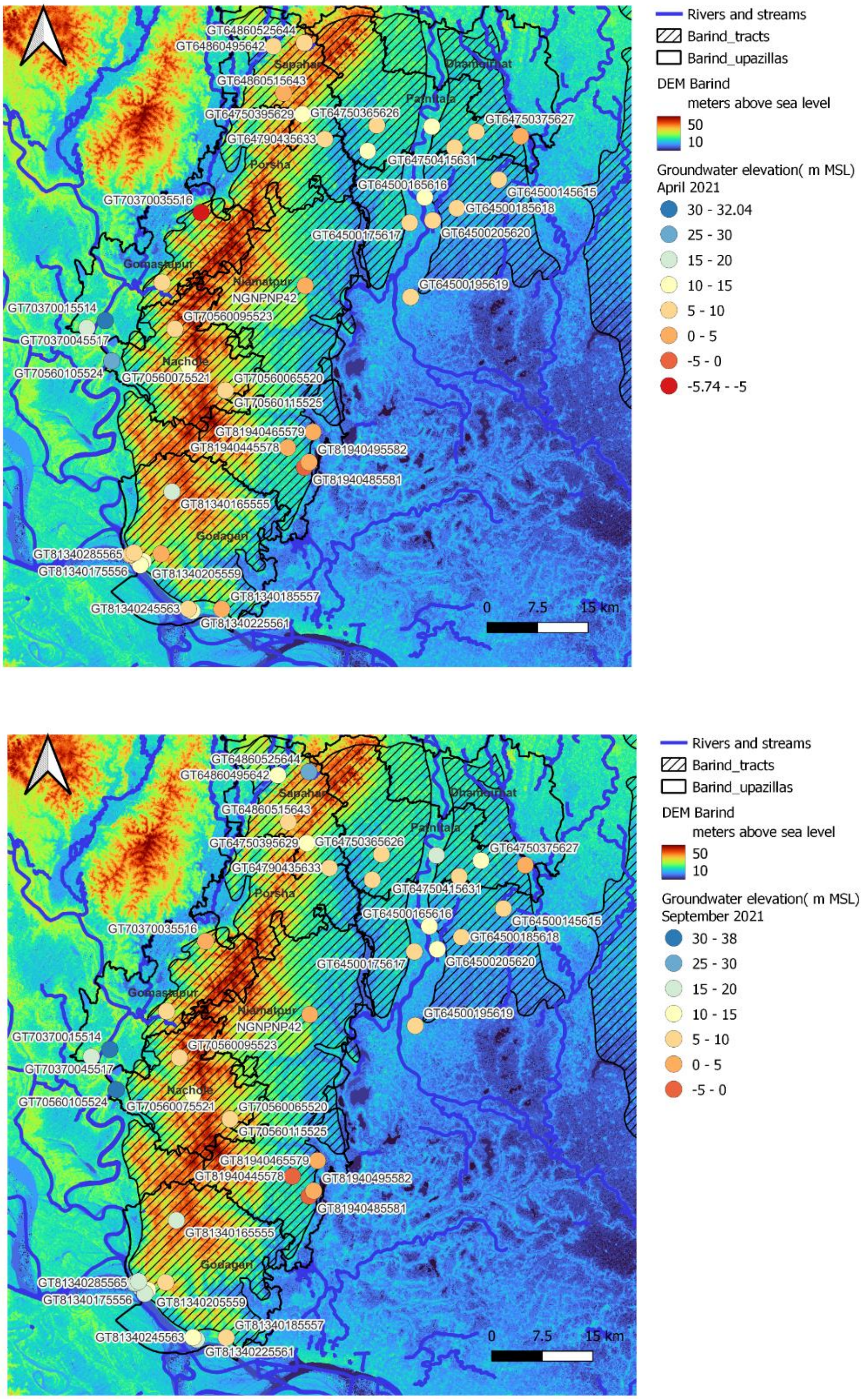


Figure 11 Spatial pattern of groundwater elevation (hydraulic head) in April 2021 (end of dry season) and September (end of monsoon system).

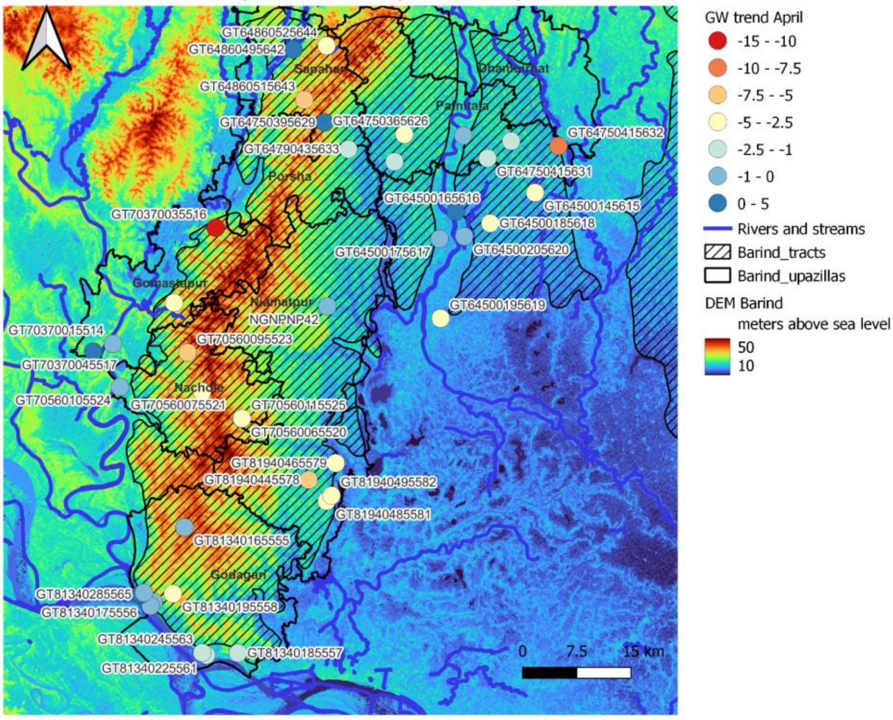
3.1.3 Spatial distribution of groundwater trends

The trends in groundwater level (Figure 12) were derived by subtracting the groundwater level of April 2010 from those of April 2021 for the dry season, and September 2010 from September 2021 for the monsoon trend. Therefore, negative numbers represent a declining groundwater table. This method could result in outliers if one of the years is not in line with the general trend. Overall, however, it gives a good indication of the trends.

The figure shows that most of the monitoring wells surrounding the high Barind and located near Rivers show no clear trend, and groundwater tables appear to remain stable in both the dry and monsoon season. On the high Barind, most wells show a clear trend, in the order of 5 to even 10 m during the 11 year period. The trend appears similar in both seasons.

Some exceptions exist to this general trend. For instance well GT81340165555 does not show a declining trend, whereas most other high Barind wells do show a trend. This could be caused by factors such as different land use in the and therefore only little irrigation, or surface sediments with a higher infiltration rate. It could also be caused by local recharge, for instance by the use of surface water irrigation or another local recharge source such as ponds filled up with water from further away.

Groundwater trend April 2021 compared to April 2010



Groundwater trend September 2021 compared to September 2010

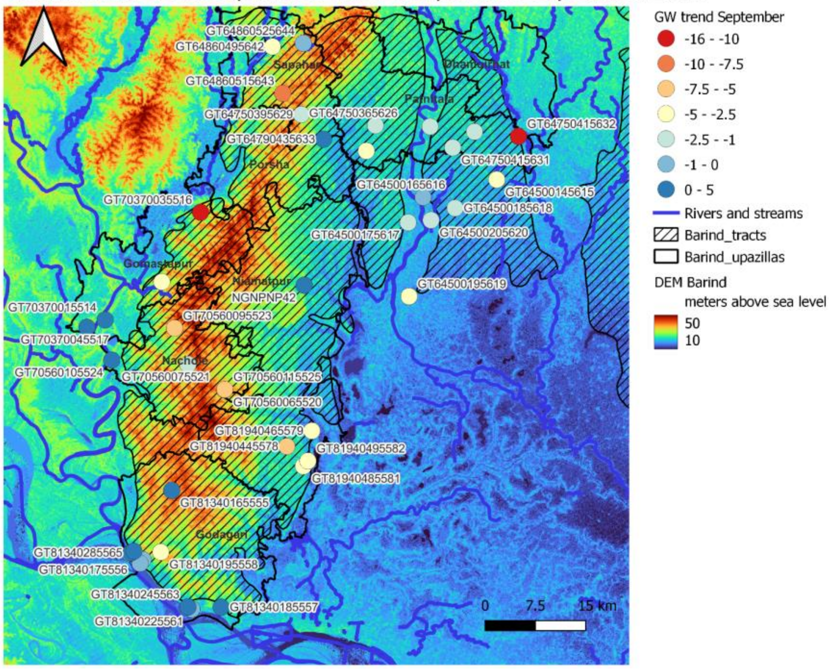


Figure 12 Spatial distribution of groundwater trends. Upper panel shows the trend in the dry season, lower panel of the monsoon season.

3.2 Discussion on groundwater trends

The trends in groundwater levels suggests that some of the wells surrounding the high Barind are installed in the channel belt deposits of the Rivers, or are installed in an aquifer that is closely connected to the channel belt. These wells have a relatively shallow groundwater table, and recover well during the monsoon season. Therefore, no declining trend is visible and at these locations no long term depletion takes place. The system of recovering wells has been coined Bengal Water Machine in a recent Science article (Shamshudda et al., 2022). However, it should be realized that, if not managed sustainably, in the dry season this could still lead to adverse effects, such as streamflow depletion during the dry season and adverse effects on other functions of the surface water bodies, such as nature, fisheries and domestic water supply.

Below the high Barind, a clear downward trend is visible in most monitoring wells, by up to about 1 m/year. Interestingly, the trend is curving, and the decline seems to go slower in time. This could be the result of recent efforts to use less irrigation water by crop changes and surface water irrigation. However, such a trend is also expected when the groundwater system adapts to the excessive extraction, and moves towards a new equilibrium in which the change in storage is met by increasing recharge from Rivers and decreasing groundwater discharge (Figure 4).

These trends are also observed by Commonwealth Scientific and Industrial Research Organisation (CSIRO) (2014), who analyzed 1200 wells across the country. In the Barind they recognize Type 1 “Both min and max are declining with little recovery”, and type 2 “both min and max are declining with some recovery”. This latter type is especially found in the south of the high Barind, towards the Ganges. They only recognize some wells, indeed near River valleys, that recover completely during the monsoon.

During both the dry season, groundwater elevations in the high Barind are still higher than the Atrai River in the east, indicating that the flow direction will be eastward. During the monsoon, infiltration takes place from the Rivers surrounding the Barind into the aquifers. Strikingly, the wells along the Mahananda River in the west show the highest groundwater elevations, which suggests that this River recharges the Barind aquifer all-year round, and the groundwater flow direction is eastward. It is expected that in the natural state, groundwater elevation below the high Barind were higher than those in the Mahananda channel belt, and naturally the groundwater flow direction was from the central high part of the Barind towards the sides.

The groundwater trends do show that below the high Barind depletion takes place almost everywhere. At some locations, the groundwater levels reach the bottom of the confining layer which could have major implications for the groundwater system. This stresses the need to investigate options to counteract the negative trends. MAR is one of the partial solutions that need investigation.

3.3 Adverse effects reported

Apart from the expected physical and natural undesired consequences related to abstraction, also socioeconomical consequences are reported. Interviews with DTW operators in Rajshahi indicate DTW depths had to be increased from time to time as groundwater levels drop well beyond 30 meters in the boro season. DTW operators in some locations in Rajshahi noted increased DTW pump breakage in the early boro season as a result of intensive use (Banerjee and de Silva, 2020; de Silva and Leder 2017). Farming communities served by DTWs have clearly benefited, but communities without access to DTWs report conditions have become more challenging, and this has potentially significant developmental implications (de Silva and Leder 2017). The overall impact is lower yields and increased irrigation costs that now constitute more than 50 percent of total production costs. Domestic hand pumps in villages also struggle during March and April each year. In the hydrographs of the Barind, many monitoring boreholes show water levels that fall below about 8 m during March, April and May. This is the critical depth below which shallow and handpump wells cannot obtain water, and therefore in these areas water has to come from other sources.

4 WATER BALANCE FOR THE HIGH BARIND

What we have seen in the previous chapter about the high Barind, is that several areas show groundwater levels that are continually declining. In other areas, groundwater levels appear to recover during the wet season even though large volumes are being abstracted. To look at the potential for different measures to achieve a more sustainable situation, such as using River water for irrigation, changes in crops, or Managed Aquifer Recharge, it is first important to understand the water balance of the region. In other words, we want to understand how much water comes into the system, how much goes out and along which ways. Once we know that, we can estimate what kind of water volumes would be desirable to be recharged by MAR measures to make a significant contribution to a more sustainable groundwater system.

To understand the water balance we need to estimate the terms of the water balance. These are:

- Precipitation
- Evapotranspiration
- Runoff
- Recharge
- Discharge (pumping, baseflow)

Many articles have been written about individual water balance terms of the Barind region. These articles are often not in agreement. It is important to include all different claims in literature and reports about the water balance terms, to be able to indicate the uncertainty in the current knowledge. The aim of this task is to list all parameters from literature and reports, and to collect other sources of data that can help in the assessment of the water balance.

4.1 Water balance according to the JCP metamodel

The metamodel constructed in the Joint Corporation Programme (JCP) (https://jcpbd.nl/bdp-metamodel/) is used to get a first impression of the water balance in the Barind for the selected upazillas. The metamodel calculates all water balance terms for each upazilla. Input are the precipitation, land use, and soil types, and based on a set of rules and assumptions the evapotranspiration, infiltration (unsaturated zone), percolation (recharge of groundwater), runoff, and required surface water and ground water irrigation to maintain the crops when not enough water is available is calculated. Because the upazillas are relatively high, no surface water is calculated for the selected upazillas and all irrigation comes from groundwater.

For this first impression, the average output values from a 33 year period from 1985 to 2017 are used (Figure 13). The average monthly data clearly shows the wet period in which most precipitation falls from April to October. During this period, most water is lost as runoff. Because crops are grown all year, evapotranspiration is a large term each month. However, to be able to grow crops, groundwater irrigation takes place from January to May. Recharge of groundwater takes place during the wet season. It should be realized that because the groundwater irrigation is calculated based on the water demand of crops, the irrigation return flow is not included. This also implies that it is expected that more groundwater is pumped up than the amount in this water balance, since that would be a combination of irrigation water plus return flow.

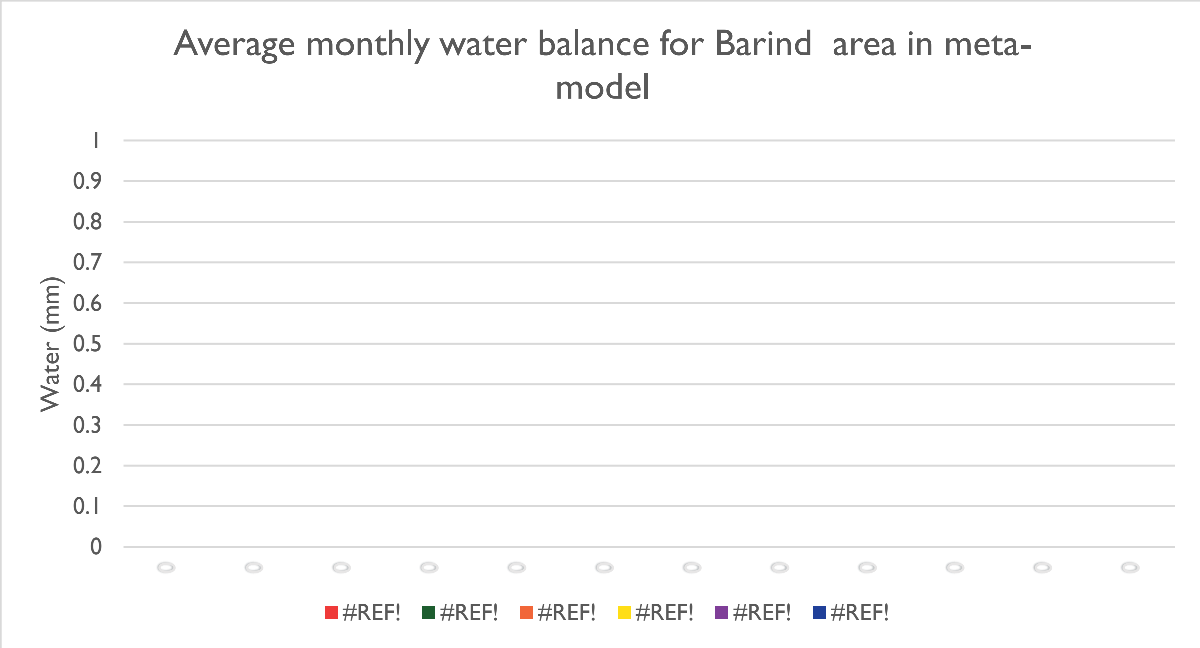


Figure 13 Average monthly water balance for the 9 selected upazillas in the Barind region for the period of 1985 to 2017 (33 years).

The average yearly water balance for the 9 selected upazillas and the total is provided in

Table 1. The table shows that according to the model, 35% of precipitation is lost to runoff, 14% goes to infiltration (soil moisture), and only 5% goes to recharge. Evaporation accounts for 75% of the precipitation, which can be explained because also the groundwater irrigation is evaporated eventually. Most upazillas have no closed water balance, which is probably due interaction with other upazillas.

Groundwater irrigation with on average 356 mm amounts to 24% of the total precipitation. This number is well in line with estimates by Adham et al. (2010) who report a historical extraction of typically 20–30 % of the annual precipitation. Since much less water is recharged in this model, this leads to a groundwater depletion of 290 mm. It should be noted that this is 56% of the calculated runoff. This would imply that 56% of the runoff needs to be artificially recharged if one wants to balance recharge and groundwater irrigation. Over 68% of the runoff needs to be artificially recharged if the entire groundwater irrigation should be compensated.

Table 1 Overview of metamodel output for the Barind upazillas. The totals are weighted averages except for the Surface area which is the total. %P stands for the percentage compared to precipitation.

Upazilla	Area (m2)	Precipitation (mm)	Evapo-transpiration (mm)	% P	Infiltration (mm)	% P	Recharge (Percolation) (mm)	% P	Runoff (mm)	% P	Groundwater irrigation (mm)	% P	Groundwater depletion (mm)	Water balance	% P
Dhamoirhat	372,939,800	1517	-1242	82	-238	16	-101	7	-444	29	474	31	373	-34	-2
Godagari	596,626,300	1310	-998	76	-165	13	-12	1	-526	40	359	27	347	-31	-2
Gomastapur	391,252,600	1391	-712	51	-113	8	-15	1	-459	33	136	10	121	229	16
Nachole	344,835,600	1439	-1070	74	-161	11	-17	1	-461	32	233	16	216	-38	-3
Niamatpur	544,092,900	1478	-1192	81	-251	17	-122	8	-418	28	419	28	297	-85	-6ss
Patnitila	474,228,800	1495	-1248	83*	-247	17	-103	7	-581	39	471	32	368	-213	-14
Porsha	325,639,100	1556	-1034	66	-242	16	-121	8	-644	41	396	25	275	-88	-6p
Sapahar	300,414,400	1536	-1030	67	-216	14	-99	6	-534	35	342	22	243	0	0
Tanore	361,443,400	1566	-1028	66	-174	11	-12	1	-660	42	319	20	308	11	1
Total	**3,711,472,900**	**1465**	**-1068**	**73**	**-201**	**14**	**-66**	**5**	**-520**	**35**	**356**	**24**	**290**	**-34**	**-2**

4.2 Water balance from literature

CSIRO et al., 2014 and Kirby et al., 2014 published approximate water balances for 8 regions, one of which was the entire northwest quarter of Bangladesh. These balances are based on a simple water balance model and climate and (irrigated) crop area input data. Their water balance seems to show a comparable annual average groundwater inflow (recharge) and groundwater outflow (irrigation applied and baseflow). This would suggest a groundwater table that recovers during the monsoon season. However, this study is for the entire northwest region, which is composed of different physiographical regions. Therefore, the calculated values are difficult to compare to other values more specifically for the high Barind.

4.2.1 Precipitation

The Barind region belongs to one of the driest regions of Bangladesh (Jahan et al., 2010). The area has a subtropical monsoon climate characterized by three distinct seasons: 1) the dry winter season from November to February, 2) the pre-monsoon hot summer season from March to May, and 3) the rainy monsoon season which lasts from June to October (Jahan et al., 2010; Shahid & Hazarika, 2010). Mean annual rainfall varies between 1310 and 1625 mm. Most precipitation falls in the monsoon period. According to Shahid & Hazarika (2010) this is almost 83% of the annual rainfall. Moreover, rainfall varies widely from year to year. In the forty year prior to the study of Shahid & Hazarika (2010) the region suffered eight major droughts. To illustrate this: the recorded rainfall at Rajshahi was 2062 mm in 1997, but was only 798 mm in 1992.

Table 2 Precipitation values reported in literature

Source	**Mean annual rainfall**	**Notes**
Rushton et al., 2020	1500 mm	
Aziz et al., 2020	1625 mm	Annual rainfall of Rajshahi district between 2000 and 2012.
Jahan et al. (2010)	1600 mm	The average annual rainfall between 1980-and 2006.
Shahid & Hazarika (2010)	1500 mm	Annual average rainfall for the period 1964-2002 recorded in a meteorological station located at Rajshahi
Metamodel (JCP, 2022)	1310 – 1566 mm	Based on BMD daily data available for 34 meteorological stations for 1985-2017. Precipitation per upazila is based on the nearest meteorological station.

4.2.2 Evapotranspiration and crop water demand

Monthly potential evapotranspiration (PET) was estimated for two districts in the research area by Jahan et al. (2010) using the modified Penman-method (1948) by Doorenbos and Pruitt (1977). Potential evapotranspiration is the sum of evaporation from the soil and transpiration by vegetation if water availability is not limiting. It mainly provides insight in the seasonal differences in evapotranspiration conditions. Figure 14 shows the potential evapotranspiration for the Naogaon district in red, as calculated by Jahan et al. (2010). Potential evapotranspiration is highest in the pre-monsoon season and lowest in winter.

The actual crop evapotranspiration may exceed or be lower than potential evapotranspiration, depending on the crop type and the water availability. Figure 14 shows the crop evapotranspiration (ET_{crop}) for Aus and Boro rice seasons, as calculated by Jahan et al. (2010) using the Michael-method (1978) for the Naogaon district. Aus and Boro refer to the winter and pre-monsoon rice seasons respectively. The figure also shows the Net Irrigation Requirement (NIR), as calculated by Jahan et al. (2010) using a field water balance. Negative values indicate a precipitation deficit, while positive values indicate a precipitation surplus. According to the analysis of Jahan et al. (2010) only by mid may – shortly before the start of the monsoon season - precipitation is insufficient to meet the Aus crop demand.

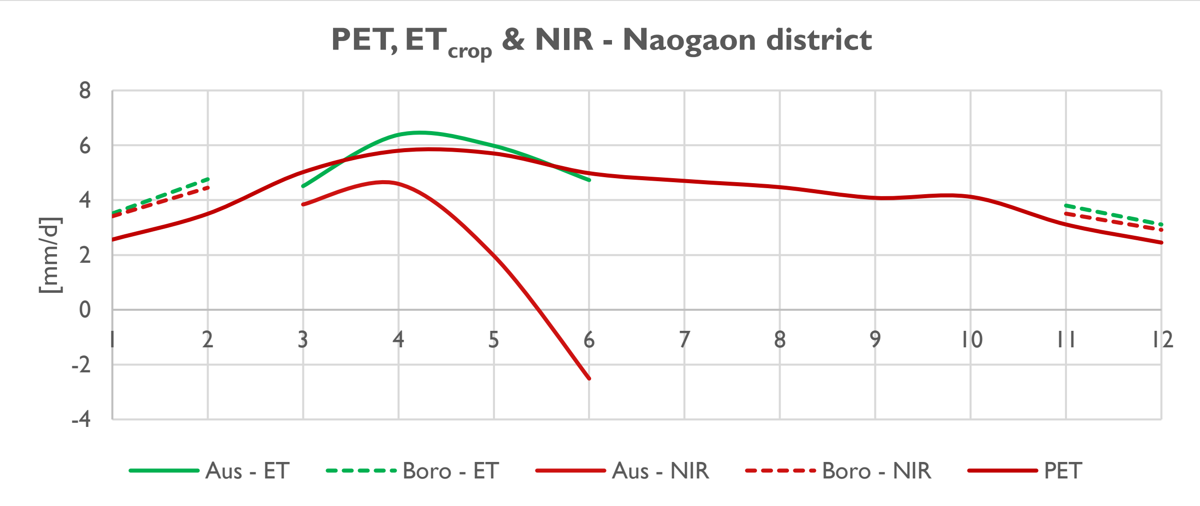


Figure 14 Crop evapotranspiration depending on crop type and water availability (Jahan et al., 2010)

An alternative approach to estimate evapotranspiration is presented by Rushton et al. (2020). They estimated the potential and actual evaporation based on the precipitation and crop-related irrigation scheme for 2017. They find that for the whole of 2017, the actual evapotranspiration equals the potential evapotranspiration, because there is sufficient precipitation and irrigation to ensure the crop water demand. Similarly, to the study of Jahan et al. (2010), Rushton et al. (2020) find that potential (and actual) evaporation is highest in the pre-monsoon season with values up to 6 mm/d and lowest in winter with values around 2 mm/d.

Kirby et al., (2014) show evapotranspiration values between 60 mm/month (Dec / Jan) and 150 mm/month (April / May), leading to a yearly average of about 1200 mm for the entire Northwest.

The only estimate for annual evapotranspiration is provided by the JCP metamodel. According to the metamodel the average annual evapotranspiration is about 1068 mm/year for the study area based on simulations for a 33-year period from 1985 to 2017.

4.2.3 Recharge

Adham et al., 2010 report a percolation rate for the Barind clay of 2mm/day, based on Institute of Water Modelling (IWM) (2006). They report that about 8.5% (144 mm) of the total average annual rainfall (1685mm) percolates into the subsurface and contributes to recharge of groundwater. They state that this value is far too small to maintain the historical extraction which is typically 20–30 % of the annual precipitation.

Shahid and Hazarika (2010) report that the BMDA estimated the groundwater recharge is about one third of the annual rainfall, corresponding to about 500 mm / year (Asaduzzaman and Rushton, 2006). Islam and Kanungoe (2005) estimated the long-term annual average recharge of 152.7 mm using water balance study and aquifer simulation modeling. Government report suggests that recharge to groundwater in the northwestern part varies from 210 to 445 mm. However, exploitation of groundwater in the area is going on the basis of one-third rainfall recharge hypothesis of Barind Multipurpose Development Project (BMDP) which is beyond the sustainable yield according to Islam and Kanungoe (2005).

There is evidence that the decayed roots of the vegetation and other disturbances provide pathways for preferential vertical flow. Alam (2020) concludes that significant vertical flows can occur through the Barind Clay (Alam, 1993; Rushton et al., 2017.

Selim Reza et al. (2011) estimate recharge for a number of upazillas using a water-table-fluctuation method to estimate recharge, which relies on an assumed constant specific yield. Their specific yield varies from 10-28%, which suggests unconfined conditions of the aquifer. Their study suggests that after 1993 discharge exceeded recharge. The numbers they report are in MCM, between 271 and 450 MCM/year. When translated to mm/year, this would result in a recharge of 320 - 630 mm/year for Sapahar and 506 – 749 mm/year for Porsha.

Islam et al. (2014) also consider some of the important processes but then use a recharge coefficient which is defined as the ratio of recharge to rainfall and expressed as a percentage. Rushton et al., (2017) report recharge (vertical flux) from the Upper Unit determined during the model refinement process likely to be in the range 1–4 mm/day (about 25–100 % of the average annual precipitation).

Rushton et al. (2020) estimate recharge through the year using an elaborate soil water balance. They recognize three periods: the first rice crop (pre-monsoon: January to April), the second rice crop (monsoon: May to September) and the post-monsoon crop (October – December) here tomato). During the rice cultivation periods, there is recharge on most days, not only on the days on which there is rainfall or irrigation. This recharge through the bunds and beds of rice fields occurs for two periods, each of about 4 months. During the post-monsoon crop, the aim is to ensure that the soil moisture deficit is small. When the irrigation results in a negative Soil Moisture Deficit, limited recharge occurs on that day.

Rahman and Roehrig (2006) show that recharge is insufficient in some parts of the area, but was just sufficient in others, and is generally in the range of 350 – 500 mm per year.

Jahan et al. (2010) distinguish three different seasons than Rushton et al. (2020), namely winter (November to February: cool and dry with almost no rainfall), pre-monsoon (March – May: hot and dry) and monsoon (June – October). Jahan et al. (2010) report a low infiltration rate of 1-2 mm/day (United Nations Development Programme (UNDP), 1992). In the northern part (Naogaon district), the extraction of groundwater for irrigation requirement is higher than the recharge, causing constrains for Boro rice paddy cultivation. For the southern part (Chapai-Nawabganj and Rajshahi districts), it is suggested that that it has suitability for further groundwater development to meet the requirement for Boro paddy cultivation (IWM, 2006).

To derive the total recharge per year from the reported recharge rates per day, also the total days of precipitation or inundation are important. Figure 15 shows the recharge per year for four different recharge rates and different number of days of precipitation or inundation. The figure shows that with high recharge rates and 250 days of precipitation and inundation, about 1000 mm of recharge can be expected. In many regions there will be more days of inundation due to irrigation of boro rice. However, the irrigation water that infiltrates into the ground is considered return flow and therefore not replenishing the aquifer (it was just abstracted from the aquifer).

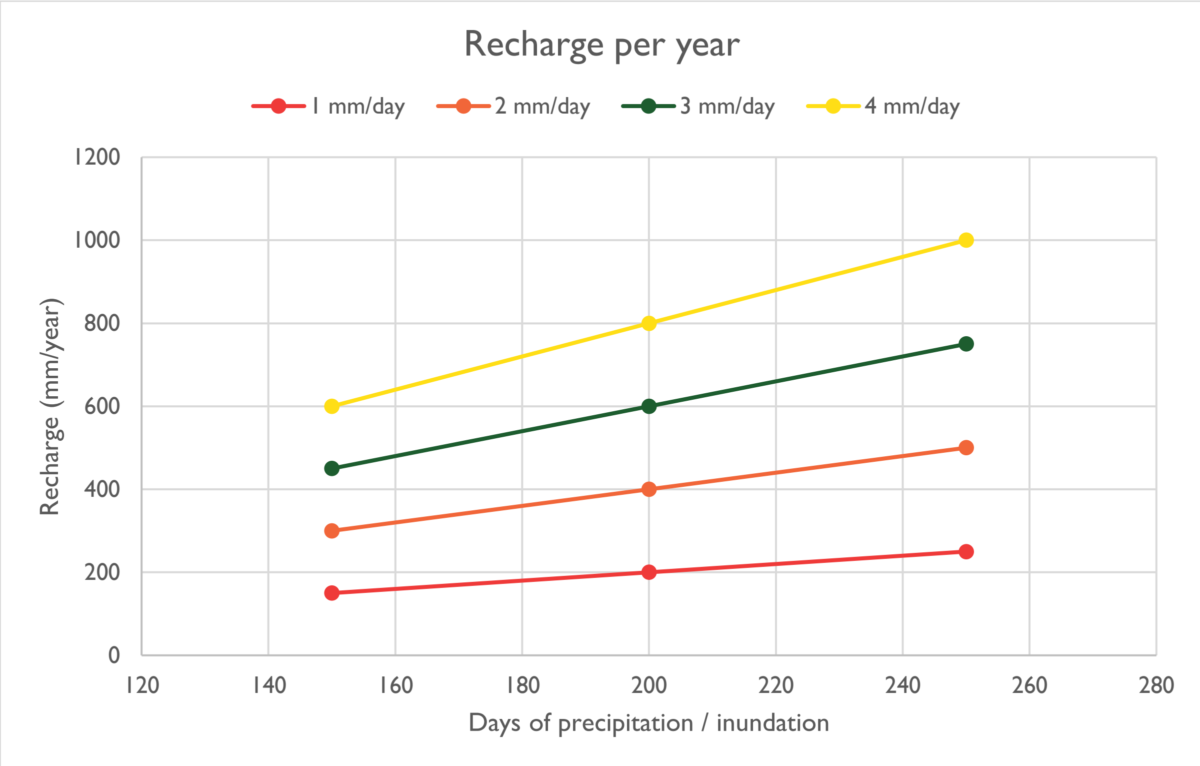


Figure 15 Yearly recharge for different reported recharge rates and scenarios of days of precipitation or (natural) inundation.

A study of IWM (2012) introduces the term *potential recharge*, which they define as the sum of actual recharge and rejected recharge. The latter is the volume of excess precipitation that is lost by surface runoff. According to the study of IWM (2012) usually in late September or October high groundwater levels prevent any additional infiltration of precipitation. IWM estimated Upazilla-wise potential recharge by simulating the monsoon period of 2001 without irrigation and an artificially low groundwater table to ensure that all the recharge from rainfall enters the saturated zone (see Table 3). To account for uncertainties in the model, IWM continues the analysis with useable recharge (75% of potential recharge). They compare useable recharge with the estimated irrigation requirement (based on crop patterns) and the estimated extraction for the year 2005 (based on number of registered wells). Their analysis shows that the Dhamoirhat, Patnitila and Tanore Upazilla's may be prone to overexploitation of groundwater, i.e. more water is extracted than recharged.

Table 3: Upazilla-wise potential recharge, useable recharge, irrigation requirement and abstracted groundwater from the study of IWM (2012). Potential and useable recharge are based on groundwater simulations for the monsoon period of 2001.

	Area (m^2)	Potential recharge (mm)	Useable recharge (mm)	Irr requirement (mm)	% of usable recharge	Actual abstracted water (estimated from DTW+STW) (mm)	% of usable recharge
Dhamoirhat	372,939,800	531	398	432	108%	429 (61)	108
Godagari	596,626,300	521	391	295	75%	151 (86)	39
Gomastapur	391,252,600	413	310	180	58%	99 (39)	32
Nachole	344,835,600	648	486	206	42%	91 (27)	19
Niamatpur	544,092,900	451	338	290	86%	175 (64)	52
Patnitila	474,228,800	390	293	286	98%	335 (46)	115
Porsha	325,639,100	358	269	105	39%	142 (45)	53
Sapahar	300,414,400	411	308	193	63%	130 (35)	42
Tanore	361,443,400	357	268	280	105%	167 (44)	62

Table 4 lists the different reported recharge value in mm/year for the consulted literature studies and literature.

Table 4 Estimated recharge values for Barind upazillas from different studies

Source	Recharge	Notes
Adham et al., 2010	144 mm	Based on remote sensing along with a geographic information system for groundwater recharge potential
Shahid and Hazarika (2010) / Asaduzzaman and Rushton (2006)	500 mm	Based on BMDA estimates that groundwater recharge is about one third of the annual rainfall
Islam and Kanungoe (2005)	153 mm	Based on water balance study and aquifer simulation modeling
Islam and Kanungoe (2005) "Government report"	210 to 445 mm	

Selim Reza et al. (2011)	320 – 750 mm	Using a water-table-fluctuation method to estimate recharge, which relies on an assumed constant specific yield
Jahan et al. (2010)	1-2 mm/day (150 – 500 mm)	
Rahman and Roehrig (2006)	350-500 mm	
IWM (2012)	268-486	Based on 75% of potential recharge according to simulations.
Metamodel (JCP, 2022)	12 – 122 mm (average 66 mm)	Based on model using water demand related to crop pattern and including soil type

4.2.4 Discharge

In a natural aquifer system groundwater discharge is the loss of groundwater due to vertical or lateral flow. This can be either flow towards a different aquifer system or flow towards the surface (often Rivers). In the present-day developed situation discharge of groundwater occurs also through pumping wells for domestic and irrigation purposes. It is extremely hard to make reliable estimations of all discharge terms, as these flows occur over large areas (partly) out of sight. However, a couple of studies have tried to quantify (some) of the terms.

As part of an extensive groundwater resource study for the wider Barind region, IWM (2012) estimated the total groundwater extraction for the year 2011 and the groundwater exchange between the Ganges and Barind aquifer system. Based on the irrigation water requirement and the number of shallow and deep tube wells, they estimated an extraction rate varying between 136 (Sapahar Upazilla) and 368 (Dhamoirhat Upazilla) mm/yr. The results of the hydrogeological model suggest a net average flow of 13.546 Mm^3 towards the Ganges. This is equal to 7.11 mm/yr if divided over the area of the adjoining upazillas (i.e. Shibganj, Nawabganj, Godagari, Paba and Charghat).

Alternatively, Reza et al. (2011) estimated the total discharge for Porsha and Sapahar Upazillas using a seasonal water-table-fluctuation method, similarly as described in the section about recharge. Their results show discharge of 350 - 922 mm/year for Sapahar (solid red line in Figure 16) and 510 – 896 mm/year for Porsha (solid blue line in Figure 16). Based on the registered number of shallow and deep tube wells and average discharge rates, Reza et al. (2011) also determined discharge rates due to groundwater extractions for domestic and irrigation purposes. These results show extraction rates of 80-140 mm/yr for Sapahar and 80-123 mm/yr for Porsha. This is about 12-29% of the total calculated discharge, demonstrating no clear increasing or decreasing trend. Due to a significant number of unregistered wells, the method of Reza et al. (2011) may underestimate the actual abstracted volume. In addition, this method is very much dependent on the location of the monitoring wells compared to cones of depression of extraction wells. If the monitoring wells are affected by the extraction, the “natural” discharge values are overestimated.

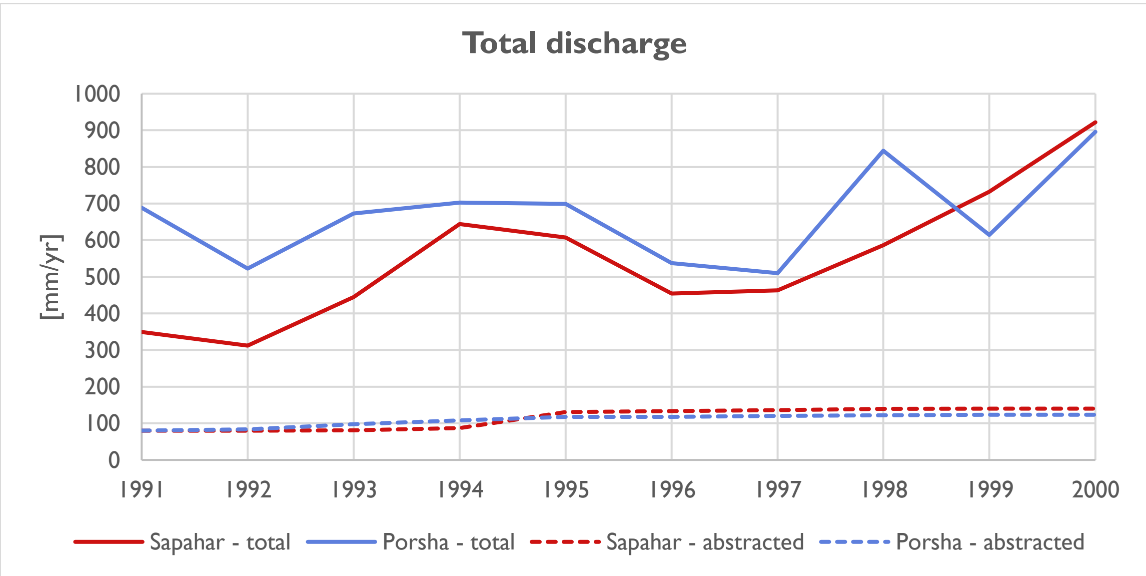


Figure 16 Discharge according to Reza et al. (2011)

The JCP metamodel also estimates the volume of groundwater abstracted for irrigation purposes. The volume is based on the proportion of crop water demand that cannot be met by surface or soil water. They find an average of 356 mm groundwater irrigation per year.

Jahan et al. (2010) report that in 2005 the total irrigation requirement was consistent with total extraction of groundwater (2256 MCM) by 6909 DTWs and 99502 STWs. This number is related to the entire Barind area of 7500 km^2, and would correspond to 300 mm of extraction for the entire area.

Based on a water demand study for Boro rice, Shamshudda (2010) report that the irrigation water demand in the northwest of Bangladesh varies between 839 mm and 1212 mm, which amounts up to 95% of the precipitation. The high Barind upazillas, however, show lower values.

Table 5 lists the discharge values by extraction reported in literature in mm/year.

Table 5 Discharge values reported in literature

Source	**Discharge by extraction**	**Notes**
Selim Reza et al. (2011)	80-140 mm	Using a water-table-fluctuation method
Jahan et al. (2010)	300 mm	For entire Barind region (7500 km^2)
IWM (2012)	136-368 mm	Actual extraction in 2005
IWM (2012)	27-86 mm	Extraction based on total use from DTW + STW
Metamodel (JCP, 2022)	136 – 474 mm (average 356 mm)	Based on model using water demand related to crop pattern and including soil type
Shamshudda (2010)	839-1212 mm	Based on water demand for Boro rice

4.2.5 Runoff

For runoff, no literature estimates have been found. It is typically the water balance term that corresponds to the precipitation – recharge – evapotranspiration. In the meta-model the runoff is calculated to be 35% of the precipitation.

4.3 Water balance conclusions

The reported values for the water balance terms of the high Barind region are widely varying, and many studies disagree. Precipitation and evapotranspiration are relatively well known, but runoff, recharge and extraction are very uncertain. This could be explained by different reasons. First of all, comparing these numbers is like comparing apples and oranges: the methods to determine them vary and each have their own assumptions. Several methods are based on the crop demand and water availability. In these methods, the deficit between availability and demand during the dry season is assumed to be the groundwater irrigation. Other studies look at water fluctuations in monitoring wells, which assumes no influence of nearby extraction wells and depends on an estimated specific yield and only vertical flow. Yet others calculate discharge by use rules of thumb for the reported number of DTWs and STWs and assume a capacity and operation time per day.

In addition, most numbers for the water balance terms are reported per upazilla. However, each upazilla consists of different physiographic regions, for instance a River plain and the elevated terraces of the high Barind. In the River plain, the abstracted groundwater can be replenished during the monsoon season (e.g. the Bengal Water Machine; Shamshudda et al., 2022), and hence recharge equals discharge in this area. However, in the elevated terraces with the thick clay layer, low recharge values are expected which will likely be much less than the amount of extracted water. Hence, in this part large groundwater depletion develops. This is also shown in Figure 9.

The meta-model output is not tested against data and therefore difficult to judge its performance. In addition, also in this model the problem exists that the output is per upazilla, and no knowledge of the physiographic system is taken into account. Hence, the recharge value can be representative for the average upazilla, while it is very high in the River plains, but very low in the high Barind. The irrigation demand is probably more spread out. Hence, the water depletion issue would go up for a smaller area, and would be more severe and urgent there.

Three-dimensional groundwater models can help to understand the water balance and indicate where problems are urgent. However, these models are also dependent on their input from water balance estimations. In addition, it is important to understand the subsurface configuration, as for instance the hydraulic connectivity of the aquifer to the Rivers plays a crucial role. Therefore, it is essential to get a better idea of the actual terms and better understanding of the groundwater system. For groundwater sustainability, important terms are the extraction of groundwater, and the natural recharge. If the abstracted groundwater in the high Barind during the dry season can be replenished entirely during the wet season, the adverse effects will be smaller.

However, it should be realized that also systems in which the abstracted groundwater during the dry season is entirely replenished during the wet season, still adverse effects can occur. For instance, due to pumping, streamflow depletion during the dry season may occur affecting groundwater dependent nature and other functions that the River delivers, such as fisheries and domestic water use.

5 MAR DESIGNS

The suitability of MAR in the Barind area is hampered by the thick clay layer at the top, which inhibits recharge during the monsoon season. When the monsoon season starts, the purpose is to collect as much water in surface water reservoirs, such as irrigation canals, ponds and paddies. Natural recharge will take place during the rainfall, and afterwards by infiltration from the ponds, canals and paddies (and the bunds in between the paddies). The ponds and paddies preferably loose little water to infiltration, because otherwise they need to be irrigated sooner when rainfall is delayed. Because of the thick clay layer, and the surface use, not many options for Managed Aquifer Recharge are available. The clay layer is too thick for infiltration ponds, and surface spreading already takes place in the current land use. One of the few methods that remains is recharge shafts or recharge wells that penetrate the clay layer and infiltrate into the aquifer.

In this chapter, we discuss three designs of Managed Aquifer Recharge in the Barind:

- Infiltration shafts/wells in irrigation channels
- MAR system along irrigation channel with pond and sand filter
- Rooftop water harvesting & infiltration

The first method consists of infiltration shafts and wells in irrigation canals. This method has already been piloted in the Barind (Hossain et al., 2021). The second method also used water from the irrigation canal, but the water is infiltrated through multiple wells after filtering through a coarse sand filter. The third method discusses roof top rainwater harvesting in combination with infiltration. Other types of MAR are also briefly discussed.

The aim of these description is to list the advantages and disadvantages of the three types, estimate the costs including operation and maintenance, and estimate the volume of recharged water per installation.

5.1 Design #1: Infiltration shafts/wells in irrigation channels

In places where aquifers are overlain by impermeable soils or the target aquifer is somewhat deep or confined, subsurface recharge methods such as injection or infiltration wells can be used for Managed Aquifer Recharge (MAR). In the Barind Tract, MAR has been implemented through recharge wells and recharge shafts installed in the *Khari* (canal) bed for infiltration of storm water during the rainy season.

A recharge well at Sormongla Khari near Paromanondopur village in Godagari Upazila (Rajshahi District), and a recharge shaft at Rasulpur Khari near Rasulpur village in Niamatpur Upazila (Naogaon District) are described in Hossain et al, 2020.

Acacia Water and Dhaka University (2015a) found that infiltration through Polyvinyl chloride (PVC pipes) (casing and screens) provides much higher infiltration rates and is preferred above infiltration through gravel. Recharge shafts filled with gravel will give lower infiltration rates over longer periods of times due to clogging. Clogging of the gravel pack and filter screen is the main reason for decreasing infiltration rates over time. In infiltration wells, clogging can be largely undone by back flushing (or jetting and surging). For that reason, recharge wells are considered more feasible than the recharge shafts. In this factsheet, the modified design of the recharge well is investigated.

5.1.1 Design

The modified design of the recharge well in an irrigation channel (Khari), at Godagari Upazila in Sormongla Khari is shown in Figure 17 (Hossain et al, 2020).

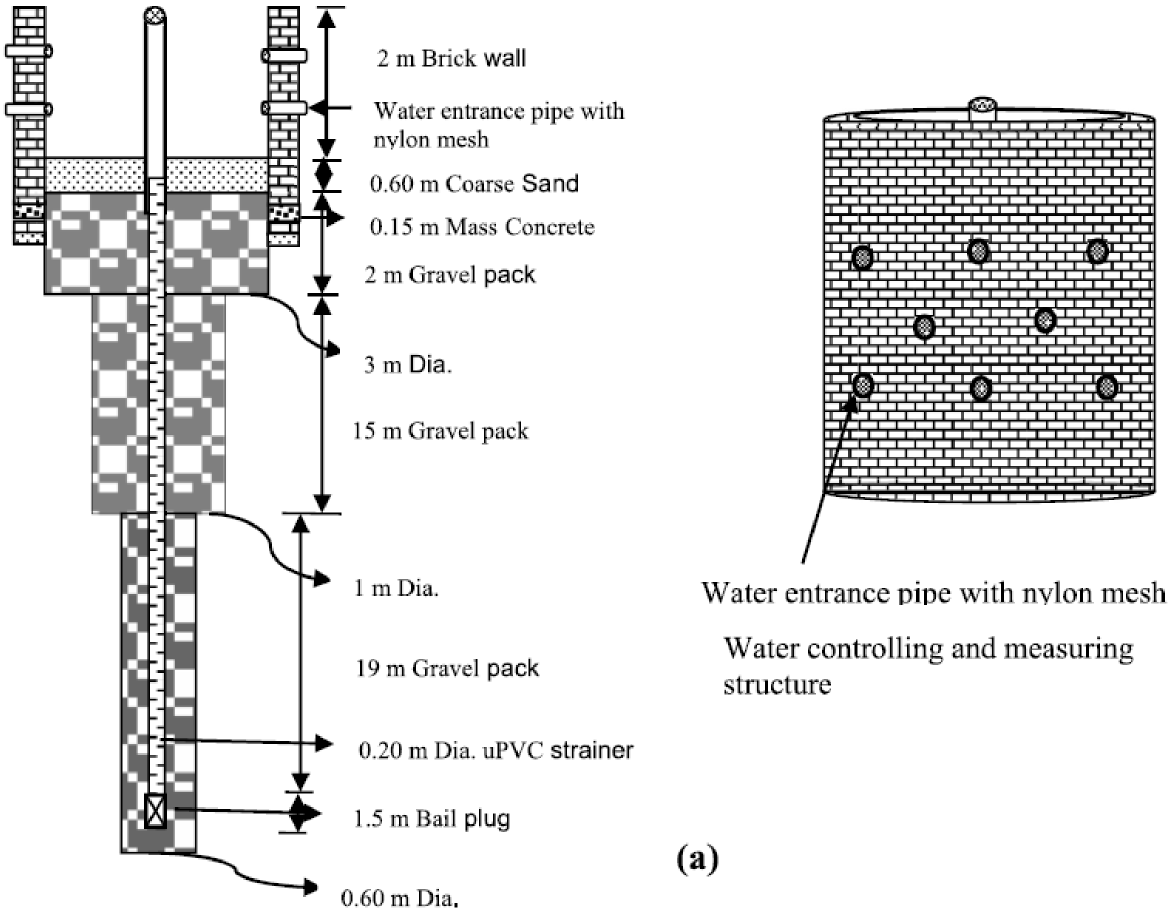

2 m Brick wall
Water entrance pipe with nylon mesh
0.60 m Coarse Sand
0.15 m Mass Concrete
2 m Gravel pack
3 m Dia.
15 m Gravel pack
1 m Dia.
19 m Gravel pack
0.20 m Dia. uPVC strainer
1.5 m Bail plug
0.60 m Dia.
Water entrance pipe with nylon mesh
Water controlling and measuring structure
(a)

Figure 17: Cross-section (above) and photo (below) of the modified design of the recharge well in an irrigation channel, at Godagari *Upazila* in Sormongla *Khari* (Hossain et al, 2020).

5.1.2 System capacity

5.1.2.1 Conventional recharge well

According to Hossain et al (2020), the recharge rate of the conventional infiltration well after construction (May 2013) was initially 48 L/min (69 m^3/day), but was found to be only 2.5 L/min (3.6 m^3/day) ten months later (March 2014), due to clogging of the recharge units with clay.

The recharge unit functions as long as water is flowing in the infiltration canals and can freely enter the entrance pipes (0.6 m height). Assuming that this is the case during the peak of the rainy season, the months June to September, this corresponds to a total of 120 effective days of infiltration a year. Assuming that the clogging took place gradually during this period and the recharge rate decreased linear correspondingly, the **system capacity** of the conventional infiltration unit was around **4,400 m^3/year/well** in the 2013 rainy season.

Each year, when the canal was dry, the clay layer (about 55 to 75 mm thick) that was clogging the recharge unit was removed, in order to restore the recharge rate. However, the monitoring data presented in Hossain et al (2020) shows that even immediately after cleaning, the recharge rate did not recover to the original rate 48 L/min in 2013, but instead was only 40 L/min in 2014 (83% of original capacity) and 29 L/min in March 2015 (63% of original capacity). And by the end of the rainy season, when a new layer of clay had formed on top of the recharge unit, the recharge rate (1.5 L/min in 2015) was found to be only 60% compared to the previous year. The **system capacity** of the conventional infiltration unit reduced to **3,600 m^3/year/well** in the 2014 rainy season and to **2,600 m^3/year/well** in the 2015 rainy season.

This suggests that clogging takes place not only by the deposition of a clay layer on top of the recharge unit when the Khari is inundated, but also by the deposition of fine silts and clays within the recharge well, in the pea gravel filter pack surrounding the uPVC strainer. The later type of clogging is much harder to remove, and as a result **the system capacity reduces 20-30% each year, despite the removal of the top clay layer each year**.

5.1.2.2 Modified recharge well

The design of the recharge well (RW) in Sormongla *Khari* was modified in 2016 in order to lower the problem of clogging by reducing the inflow of clay, and by making it possible to remove the clay layer also during the rainy season (not only when the canal is dry). The modified design includes a 2 m height brick wall surrounding the infiltration well, where water can enter through entrance pipes at 0.6 m height and at 0.15 m interval, which are covered by nylon mesh and can also be capped (to allow maintenance and cleaning inside).

The monitoring data of the modified RW presented in Hossain et al (2020) suggest that after modification, in dry condition, so before inundation of the canal, the recharge rate was 45 L/min in June 2016, which reduced to 42 L/min in March 2017 and 39.5 L/min in March 2018. In July of the same years, in the middle of the rainy season when the canal was filled with water, the recharge rates were 29.5 L/min in 2016, 28.1 L/min in 2017 and 28.0 L/min in 2018.

However, the data does not show whether recharge rates declined during the rainy season and how much. It is also not clear if and how often maintenance works such as the removal of clayey layers, washing of the sand layer and/or back flushing of the recharge well took place during this period.

Assuming a constant recharge rate of 28 L/min during 120 effective infiltration days, the system capacity of the modified recharge would be around **4,800 m^3/year/well**.

However, regular cleaning and maintenance of the surface sand layer as well as regeneration of the infiltration well (to clean the pea gravel layer and well screen) would be required on a very regular basis, in order to maintain this recharge rate during multiple years.

5.1.3 Cost estimation

According to Mr. Iquebal Hossain (personal communication), the total construction costs of a modified recharge well in a *Khari* is estimated to be around BDT 380.000,- / EUR 4.000,-.

The yearly operation and maintenance costs are expected to be around BDT 80.000,- / EUR 830,- per year.

5.1.4 Advantages and disadvantages

5.1.4.1 Which problem does it solve?

- Groundwater levels in the Barind are declining. Due to low infiltration capacity of the thick surface clay layer, the monsoon rainwater in the irrigation canals (Khari) does percolate to the groundwater only at a very low rate. The recharge of the aquifers underlying the Barind can be enhanced artificially through construction of recharge wells installed in the canal bed that penetrate the top clay layer and reach the sandy layer underneath.
- If applied on a large scale, it can also reduce soil erosion and flood hazards by reducing the flow of storm water in the canals.

5.1.4.2 Where would it be useful?

- In the Khari (canals) throughout the Barind
- Preferably in combination with check dams in the Kharis, for longer period of water availability

5.1.4.3 What are the advantages?

- Small foot print (construction and operation)
- No pumping (no fuel, no energy) required in operation
- Low construction costs
- It does not require any additional space/land area
- It can be applied on a large scale relatively easily, and as such potentially have a large impact in reducing groundwater depletion in the Barind
- If applied on a large scale, it can also reduce flood hazards in times of high water level in the irrigation canals
- In case of a Khari fed by a perennial canal or River, surface water can be infiltrated all year.

5.1.4.4 What are the disadvantages?

- It can be constructed in extraction canals only, which in general does not necessarily correspond with the locations where groundwater depletion is highest
- High turbid storm water or contaminated water can enter the (modified) recharge unit through the water entrance pipes (or when the water overflows the brick structure and inundates the recharge unit).
- The system is always working, and there is no possibility to divert the water or avoid unwanted infiltration of low quality water. As a result, the quality of the groundwater might deteriorate and the aquifer could get contaminated
- The surface water in the canals will be available for a shorter amount of time, which may mean that groundwater pumping needs to start earlier
- The recharge rate will reduce over time due to clogging of the recharge units with clay. The top sand layer of the recharge structure can be washed or replaced by new sand, but this needs to be done at a regular time interval for continuous operation of the MAR system.
- Clogging of the infiltration well and pea gravel surrounding the filter will take place over time. Regeneration of the infiltration well would be required on a regular base.
- The quality of the infiltrated (canal) water might be poor and not suitable for human consumption.
- The actual recharge rate during operation cannot be monitored properly. Also the monitoring of increasing groundwater level is difficult, which would require the placement of an additional observation tube within the recharge unit.
- Recharge head differences may be small due to groundwater upcoming below the infiltrating canal. This will lower the infiltration rate.
- Using similar infiltration units in existing ponds, to further enhance groundwater recharge, is probably not useful, because the ponds are constructed to infiltrate as little water as possible

5.2 Design #2: MAR system along irrigation channel with pond and sand filter

The second design involves an infiltration well-field along irrigation channels or along existing ponds. The advantage of this method is that water intake can be controlled and for instance only be activated when surplus of water is available or the water quality is sufficient or turbidity is low. In addition, filtration through sand filter before injection prevents clogging and an open casing and screen facilitate recharge and periodical cleaning. This design can also be implemented away from the source water with pipeline infrastructure in between the water source and the location of infiltration. This way the water could in theory be transported to the locations with the highest groundwater depletion, for instance near existing deep tube wells. Only the option near an irrigation canal is discussed here.

5.2.1 Design

NB. Infiltration only, extraction wells optional

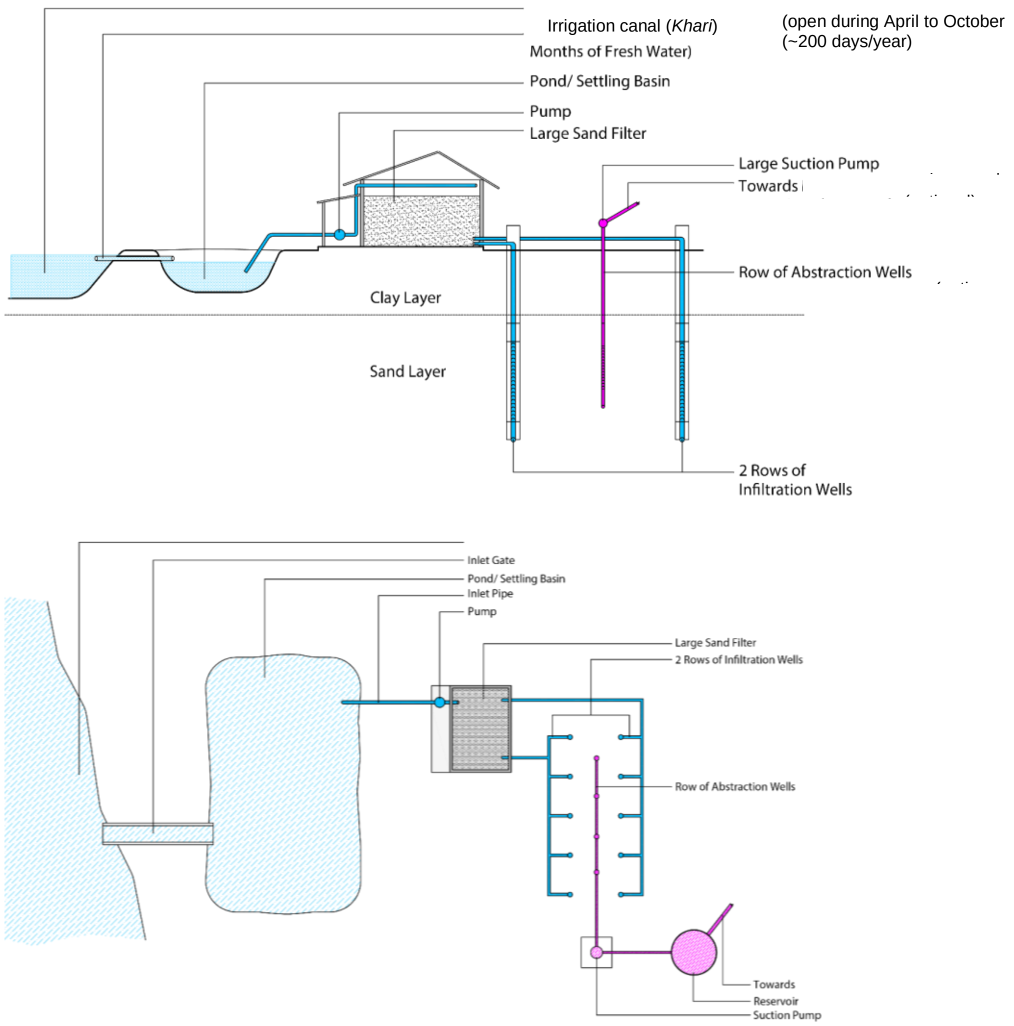


Figure 18: Concept Design of MAR system with water intake from irrigation channel, through settling basin and sand filter; above: sectional view, below: top view.

Prior to construction of the MAR scheme, a test drilling is foreseen in order to verify the thickness of the clay layer and the sandy aquifer underneath. An observation tube should be installed in the test well, which can be used as monitoring well during operation.

More details of the various components can be found in the MAR-CAB design report (Acacia Water, 2021).

NB. For drinking water purposes, the source water quality should be EC <2 mS/cm, Turbidity <10 NTU, Arsenic <0.05 mg/l (Acacia Water, 2020).

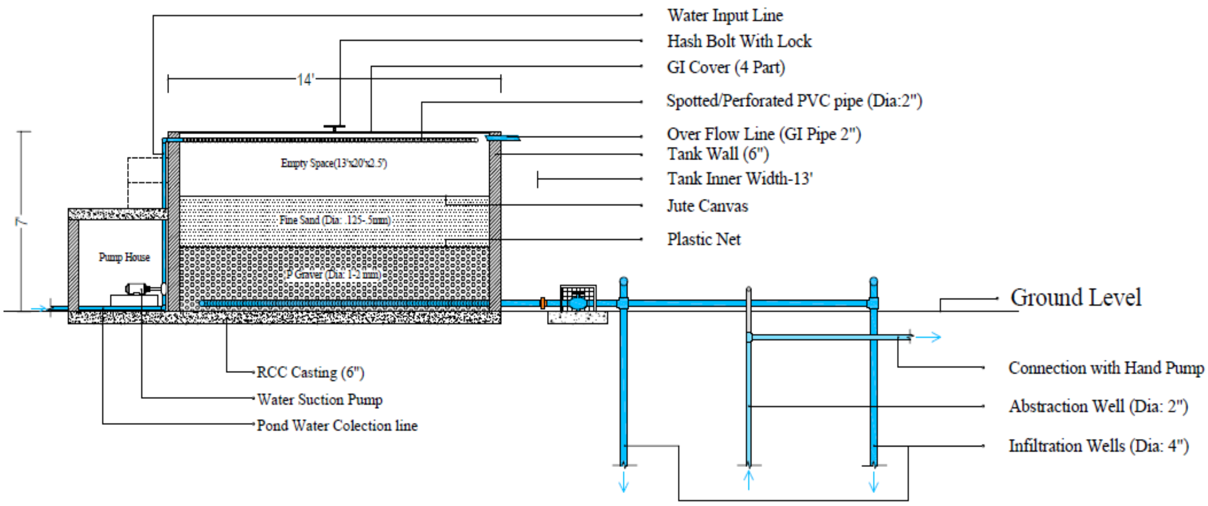


Figure 19: Cross section of the sand filter.

5.2.2 System capacity

5.2.2.1 Calculation of theoretical infiltration capacity

Assumptions:

- Infiltration days per year: 200 days
- excess water available from April – October (Rushton et al., 2020)
- Infiltration hours per day: 12 hours/day
- pump switched on/off manually early morning/evening
- Infiltration well diameter: 4 inch
- Depth to groundwater level: 5 / 10 / 20 m
- Assuming an average waterlevel in the sand filter of 1 m above groundlevel (agl), and a groundwater level in the Barind ranging between 4 m bgl (min) to 19 m bgl (max), depending on the location.
- Screen length in aquifer: 10 m
- Aquifer conductivity: 10 m/day
- Well efficiency: 50%
- Head losses in the well (screen, gravel pack) with respect to immediate surrounding aquifer. Expected to range between 30% and 100%.

With the assumptions above, the theoretical infiltration capacity would be **7.4 m^3/hr/well** (Jacob-Cooper equation) at places with a depth to groundwater level of 5 m. For a MAR system consisting of **10 infiltration wells**, this corresponds to a capacity of 74 m^3/hr or **180.000 m^3/year**.

If the depth to groundwater level doubles (10m) or quadruples (20m), the theoretical infiltration capacity also doubles (**14.9 m^3/hr/well**) or quadruples (**29.8 m^3/hr/well**).

5.2.2.2 Infiltration capacity based on experience

Monitoring data (unpublished) of the 75 United Nations International Children's Emergency Fund (UNICEF) MAR systems in three coastal districts in Bangladesh (Khulna, Bagerhat & Sathkira) show an average infiltration capacity of the MAR systems (consisting of 4 to 6 infiltration wells each) of 750 m^3/year between construction in 2015 and April 2019. These systems infiltrate during 100 days a year on average and for 8 hours a day, which means that the infiltration capacity in reality was only 0.2 m^3/hr/well. With an excess head of 5 m to 20 m in the Barind, compared to ca. 2 m in the coastal districts, this would correspond to an **expected infiltration capacity of 0.5 to 2.0 m^3/hr/well in the Barind**.

This is still much lower than the theoretical infiltration capacity (paragraph 2.3.1).

Note that the **actual infiltration rate is decreasing over time**, due to:

- the rise in piezo metric level around the well(s) will lower the depth to groundwater level, lowering the excess head
- the lowering of the water level in the reservoir (sand filter) will lower the depth to groundwater level (unless the water level is kept constant, with a pump that is automatically switched on/off using a floater)
- The infiltration capacity of the well(s) will decrease over time due to clogging of the gravel pack. This can be (partly) countered by regular well regeneration / back flushing.
- The infiltration capacity of the sand filter will decrease over time due to a mud cake being formed on top of the sand filter. This can be countered by regular cleaning and renewing of the sand filter.

Evaluation of 20 pilot schemes, prior to the construction of 75 UNICEF MAR systems, showed that mud and other fine particles present in the filter have a high impact on the infiltration capacity. Immediately after construction, the capacity of infiltration wells was found to be on average **1 m^3/hr/well**, with an excess head of ca. 2 m, but this infiltration capacity diminishes quickly over time due to mechanical or chemical clogging (Acacia Water and Dhaka University, 2015a). Testing shows that a mud cake, clogging the gravel pack, is the main factor causing poor infiltration rates. Therefore percussion drilling is advised, although slightly more expensive, this method requires less or no drilling mud at all and reduces the clogging risk. Infiltration wells should also be properly developed after installation (jetting and surging) and also regularly cleaned.

With optimal design, construction, operation and maintenance of the infiltration wells, a realistic infiltration capacity of 2.5 m^3/hr/well (with 5 m excess head) to 10 m^3/hr/well (with 20 m excess head) is assumed.

For a MAR system consisting of **10 infiltration wells**, this corresponds to a capacity of **25-100 m^3/hr** or **60.000 – 240.000 m^3/year**.

5.2.2.3 Filtration capacity of the sand filter

In reality it is often not the capacity of the infiltration wells, but rather the capacity of the sand filter (and water storage tank) that is the limiting factor in the infiltration capacity of a MAR system (Acacia Water and Dhaka University, 2015b).

The design, operation and maintenance of the sand filter have been optimized during the testing period (Acacia Water and Dhaka University, 2015a), for example by including the use of jute canvas to improve the cleaning process. The design presented in Figure 19, with a sand filter tank of 14 x 21 x 7 ft. (outer length x width x height) or 27 m^2 infiltration area turns out to function well for infiltration rates of 5 up to 10 m^3/day Acacia Water and Dhaka University, 2015b). This means that the expected filtration rate of this type of sand filter is 0.2 m/hr to 0.4 m/hr.

With optimal design, construction, operation and maintenance of the sand filter, **a filtration rate of 0.4 m/hr is expected.** This means that for a MAR system with 10 infiltration wells, **a sand filter of 62.5 m^2 (for 25 m^3/hr) to 250 m^2 (for 100 m^3/hr) is required.**

5.2.3 Cost estimation

A cost estimation for a MAR system next to an irrigation channel with a pond and sand filter and 10 infiltration wells (no extraction wells) is given in the table below.

Table 6. Cost estimation MAR system along irrigation channel with pond and sand filter

Component	Description	Amount
Pump and pump house	Electric pump (2.5 hp), electric lines, pump house construction	BDT 50,000
Sand filter	Sand filter construction (673 ft^2 / 62.5 m^2), bricks, pea gravel, fine sands, jute canvas, plastic net, roof, padlocks, hash bolts	BDT 500,000
Test drilling and installation of 1 monitoring well	Manual drilling (150 ft / 46 m / 4" dia), pipe installation (2" dia) and well cleaning	BDT 30,000
Drilling and installation of 10 infiltration wells	Percussion drilling (150 ft / 46 m / 8" dia), pipe installation (4" dia), placement of pea gravel filter pack and well development	BDT 750.000
Pipe works	PVC blind pipes and 4" screens (infiltration wells), connection pipes and caps and joints between canal – pond - filter - wells, check valves, flow meter	BDT 300,000
Civil works	Foundation building and construction materials, such as bricks, sands, cement, iron rods	BDT 450,000
Man power	Mason (60 man days), Labor (300 man days; incl pond digging), Mechanic (6 man days)	BDT 300.000
Transport	Transport of materials from markets to MAR site	BDT 180.000
Total		BDT 2.560.000

The total construction costs are estimated to be BDT 2.560.000,- / EUR 26.000,-.

Detailed cost specifications for various MAR types as well as instructions for operation, maintenance and monitoring can be found in the MAR-CAB project guidelines (Acacia Water, 2021). As an example, the table in **Error! Reference source not found.** shows the detailed cost estimation of a small-scale rural or (peri-)urban drinking water supply MAR system for 25 – 50 people.

5.2.3.1 Operation and maintenance

In addition, operation and maintenance costs are required for fuel and electric bills, minor repairs and caretaking, servicing of the pumps, and especially the maintenance and cleaning of the sand filter and infiltration wells.

The jute canvas/mesh and the top layer of the sand filter have to be washed or replaced regularly when infiltration in the sand filter drops noticeably (e.g. less than 4 in./h). How often this needs to be done depends on the turbidity of the pond water. Once or twice per year the entire sand and gravel should be taken out of the tank for washing.

Back flushing of the infiltration wells needs to be done once a month or when the infiltration capacity of a well decreases noticeably. Back flushing is detrimental for ensuring long-term functioning of the MAR system and can be done with a regular suction motor pump by pumping from the well at maximum pumping capacity for 15 minutes. If back-flushing fails to bring an infiltration well back to acceptable infiltration rates other well regeneration methods are available (e.g. air lifting, plunging, chemical treatment) which should be carried out by an experienced driller.

Another important aspect of maintenance is to ensure good water quality of the water source by e.g. stabilizing the banks of the pond to reduce turbidity.

The yearly operation and maintenance costs are expected to be Bangladesh taka (BDT 250.000),- or EUR 2.600,- per year.

5.2.4 Advantages and disadvantages

5.2.4.1 Which problem does it solve?

- It can be applied on a large scale, along the irrigation channels, and as such can locally or even regionally counter groundwater depletion in the Barind
- The reduction of the recharge rate due to clogging of the recharge units with clay
- The major problem of the infiltration shafts/wells in the irrigation channel (Factsheet 1), is during monsoon period after submergence of Khari (infiltration channel), thick clay are deposited on top of the sandy layer in the recharge structures, clogging the infiltration shaft/well and reducing the recharge rate drastically.
- This design significantly reduces the problem of clogging. The two additional steps of settling basin/pond and sand filtration reduce the suspended solids load (turbidity) of the water that is infiltrated in the infiltration well. Maintenance and cleaning of the sand filter is still required though.

5.2.4.2 Where would it be useful?

- It can be applied everywhere in the Barind along irrigation channels with good quality water

5.2.4.3 What are the advantages?

- Water purification (through sand filter) → water quality will improve

- With the pond (as settling basin) and sand filter in between canal intake and infiltration well, clogging will take place at a much lower rate and recharge rate will remain higher
- Could also be combined with extraction wells for drinking water supply (with the advantage of including operational and seasonal storage
- Recharge capacity will be much higher than the irrigation channels and also higher than infiltration shafts (factsheet 1)
- Relatively large infiltration capacity
- Design has been tested and optimized (Acacia Water and Dhaka University (2015a & 2015b)

5.2.4.4 What are the disadvantages?

- It requires thorough Operation and Maintenance (both technical and financial challenge)
- Space is required for construction of the pond and sand filter and infiltration wells
- Total investment costs are high
- Pumping is required during operation, at all times between pond and sand filter, and in case of relatively low water levels also between irrigation channel and pond
- Even the sand filter does not remove all types of contamination (in case water is abstracted for further use).

5.3 Design #3: Rooftop water harvesting & infiltration MAR

Small-scale MAR system suitable for (peri-) urban and rural communities of the Barind. Precondition is the availability of 15 x 15 ft. of land for construction and a roof area of 3,000 square feet (e.g. 100 x 30 ft.) or more from which infiltration water can be harvested during the rainy season.

5.3.1 Design

Rainwater is collected from a rooftop (e.g. concrete, sheet metal) by rain gutters surrounding the roof, which are connected to the buffer storage tank with PVC pipes. A pipe for discharging the dirty first flush of harvested rainwater after a dry period leads away from the roof. A gate valve is used to divert the first flush from the rain gutters to the discharge pipe. The discharge pipe also acts as an over flow drain for the storage tank. Two infiltration wells are connected to the tank via a PVC pipe with a flow meter and a gate valve. The connection needs to be air-tight so that no overhead pressure from the tank to the groundwater level is lost. Each well is equipped with a closed end cap at the bottom and a screw-on cap at the top (access for later well development) (Figure 20).

This system can be used in combination with a small Polyethylene tank (PE) Tank (for water supply in rainy season) and a small diameter well with hand pump (for water supply in dry season) in which case the community can have access to water all year round.

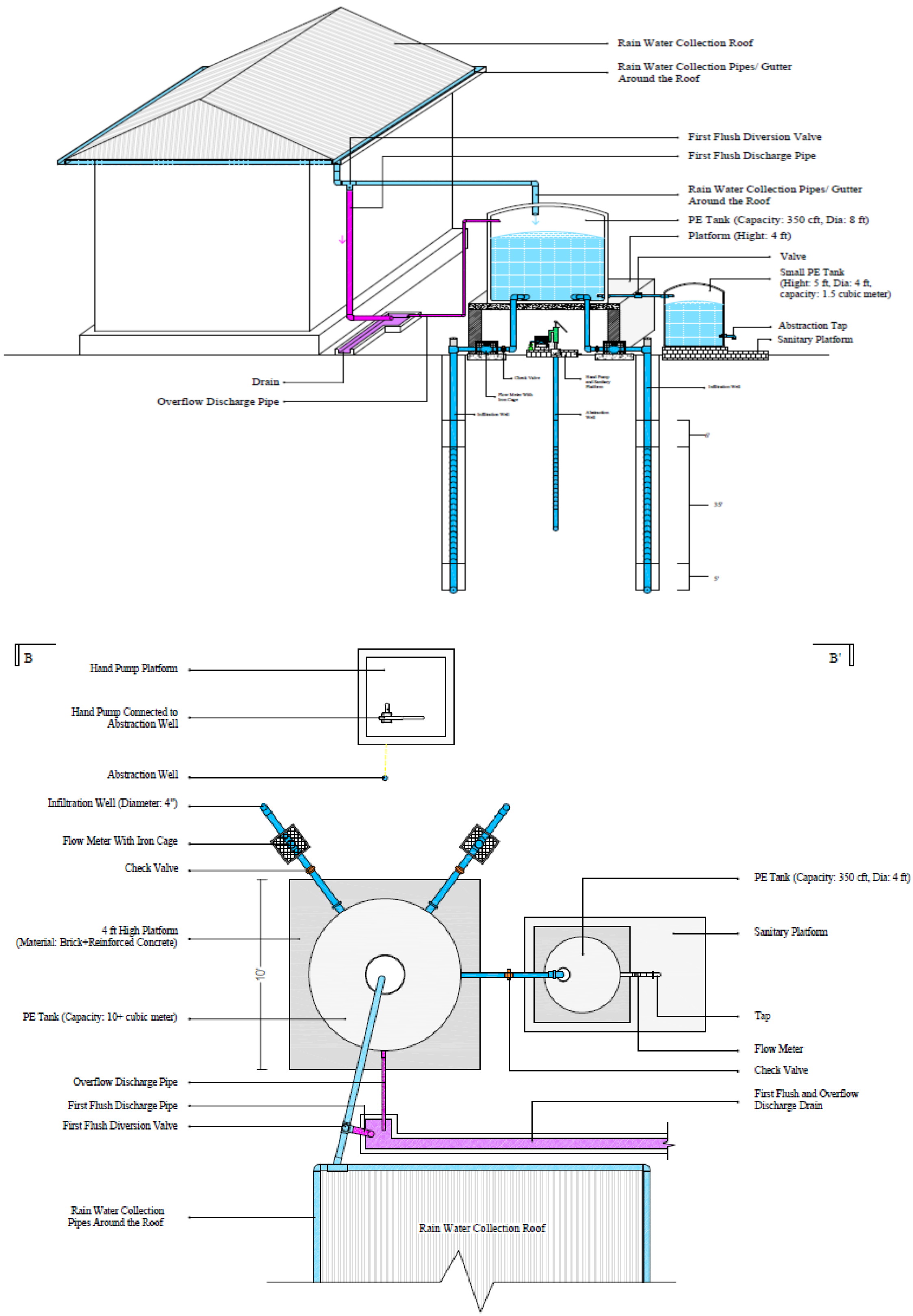


Figure 20: Concept Design of MAR system with rain water collection roof, collection tanks, and infiltration and extraction points; above: sectional view, below: top view.

Prior to construction of the MAR scheme, a test drilling is foreseen in order to verify the thickness of the clay layer and the sandy aquifer underneath. An observation tube should be installed in the test well, which can be used as monitoring well during operation.

5.3.1.1 Conventional rooftop rain water harvesting

Alternatively to the modified design shown above, a basic version of rooftop water harvesting and infiltration can be used as well. In this basic version, such as installed at Mohonpur BMDA zonal office campus in 2016, rainwater is only infiltrated and no option of extraction or storage and direct water use is included. As infiltration takes place by 1 infiltration well only, without storage tank, the advantage of this system is clearly in the low costs and low footprint. Disadvantages are that without storage tank, during medium and heavy rain storms, large parts of the rainwater harvested cannot be infiltrated and has to be 'disposed'. Another disadvantage is that the harvested rainwater cannot be stored or abstracted for human consumption. With 1 infiltration well, the total volume of water infiltrated is also low(er).

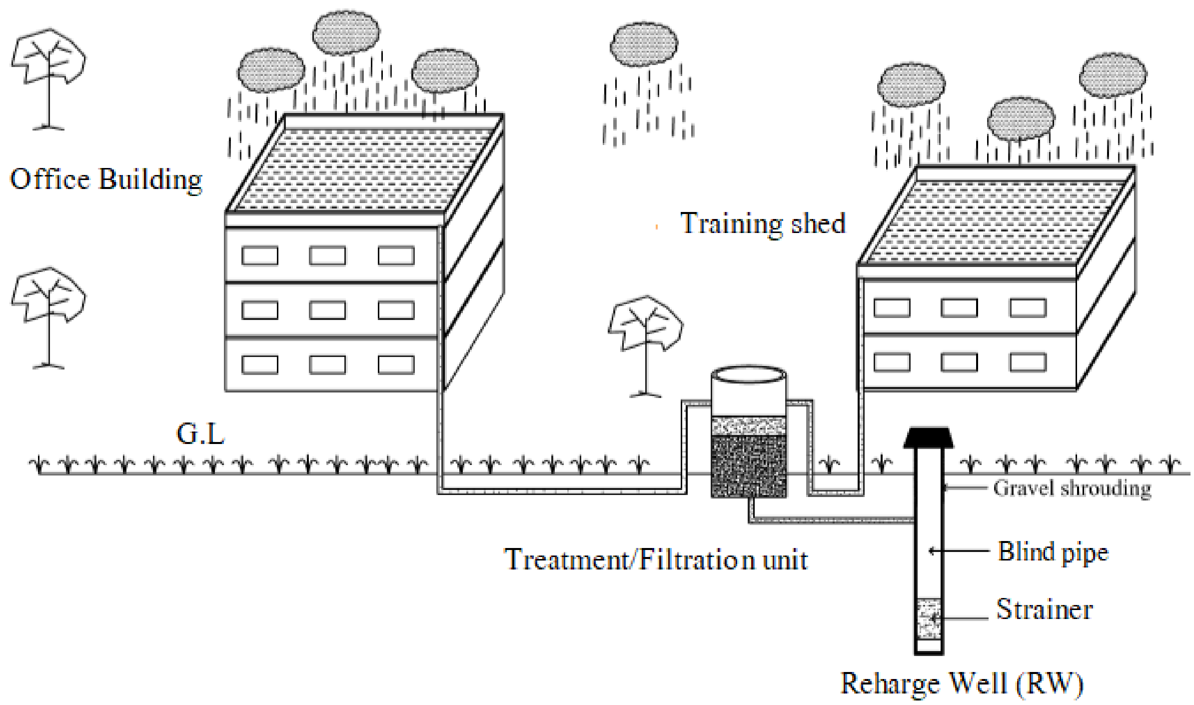


Figure 21: Design of a rooftop rain water harvesting and groundwater recharge system at BMDA zonal office campus at Mohonpur (Hossain et al, 2021a).

5.3.2 System capacity

5.3.2.1 Calculation of theoretical infiltration capacity

Assumptions aquifer and well dimensions (see explanations in 2.2.1):

- Infiltration well diameter: 4 inch
- Depth to groundwater level: 5 m (at some places: 10 to 20 m)
- Screen length in aquifer: 10 m
- Aquifer conductivity: 10 m/day
- Well efficiency: 50%

With the assumptions above, the theoretical infiltration capacity would be **7.4 m^3/hr/well** (Jacob-Cooper equation) at places with a depth to groundwater level of 5 m. If the depth to groundwater level doubles (10m) or quadruples (20m), the theoretical infiltration capacity also doubles (**14.9 m^3/hr/well**) or quadruples (**29.8 m^3/hr/well**). With the design of 2 infiltration wells (paragraph 3.1), the theoretical infiltration capacity of the MAR system is **14.9 m^3/hr** with 5m excess head.

Assumptions rainwater harvesting:

- Annual rainfall in the Barind varies from minimum of 631 mm to a maximum of 2452 mm, with an average of 1290 mm (Hossain et al, 2021a; based on rainfall records from 2002 to 2019)
- Maximum daily rainfall event: 92 mm/d (Hossain et al, 2021a)
- Rainwater harvesting factor: 90% (Hossain et al, 2021b)
- Roof area >3000 ft^2 (279 m^2), e.g. 100 x 30 ft, with a rain gutter surrounding the roof

With the assumptions above, **the discharge during a max rainfall event is 13 m^3/hr**, which can mostly be stored in the 10 m^3 PE storage tank. Even if the infiltration capacity of the wells drop to a more realistic rate of 2.5 m^3/hr/well (see paragraph 2.2.2), a total of 15 m^3 of rainwater can be stored per hour (5 m^3 underground and 10 m^3 in the tank, assuming the tank was empty prior to the rain event). In this way, all rainwater will be harvested and used to recharge groundwater.

The annual harvested volume of rainwater with a >3000 ft^2 roof is 283 m^3/year.

This corresponds with other findings of rainwater harvesting in the Barind, for example at BMDA Mohanpur office where during the years 2017 to 2019 with on average 1120 mm/year total rainfall on average 262 m^3 / year of rainwater was collected and infiltrated using 260 m^2 of roof catchments (Hossain et al, 2021b).

5.3.3 Cost estimation

A cost estimation for a rooftop water harvesting with 2 infiltration well MAR system is given in the table below.

Table 7. Cost estimation rooftop water harvesting & infiltration MAR

Component	Description	Total amount
Rainwater collection and storage	PE storage tank (350 ft^3 / 10 m^3), gutter line (incl gate valve) and water diversion (incl T-connector)	BDT 90,000
Test drilling and installation of 1 monitoring well	Manual drilling (150 ft / 46 m and 4" dia), pipe installation (2") and well cleaning	BDT 30,000
Drilling and installation of 2 infiltration wells	Percussion drilling (150 ft / 46 m and 8" dia), pipe installation (4") incl placement of pea gravel filter pack and well development	BDT 150.000
Pipe works	PVC blind pipes and screens (infiltration wells), connection pipes, caps and joints, flow meter	BDT 50,000
Civil works	Platform construction (incl bricks), construction sand and cement	BDT 80,000
Man power	Mason (20 man days), Labor (100 man days), Mechanic (2 man days)	BDT 80.000
Transport	Transport of materials from markets to MAR site	BDT 60.000
Total		BDT 540.000

The total costs (excluding yearly operation and maintenance costs) are estimated to be BDT 540.000,- (EUR 5.500,-).

5.3.3.1 Operation and maintenance

A dedicated caretaker should be in charge of day-to-day operation. During the rainy season as much water as possible should be infiltrated. In addition, operation and maintenance costs are required for minor repairs and caretaking, and the cleaning of the storage tank, rain gutters and infiltration wells.

Back flushing of the infiltration wells needs to be done when the infiltration capacity of a well decreases noticeably. Back flushing is detrimental for ensuring long-term functioning of the MAR system and can be done with a regular suction motor pump by pumping from the well at maximum pumping capacity for 15 minutes.

The rain gutters and storage tank need to be cleaned from debris before each rainy season or whenever they are clogged.

The yearly operation and maintenance costs are expected to be BDT 5.000,- or EUR 51,- per year.

Detailed cost specifications for various MAR types as well as instructions for operation, maintenance and monitoring can be found in the MAR-CAB project guidelines (Acacia Water, 2021).

5.3.4 Advantages and disadvantages

5.3.4.1 Which problem does it solve?

- Natural recharge of groundwater in the Barind mainly depends on infiltration of rainwater, but the >15 m thick Pleistocene clay is low permeable (infiltration capacity is 2-3 mm/day) and acts as a main barrier of natural recharge. This means that in the current situation, excessive rainwater hardly reaches the groundwater but instead leaves the area as surface runoff.
- Local recharge of groundwater through infiltration of rainwater harvested on rooftops will locally/partly counter groundwater depletion in the Barind
- Rooftop rainwater harvesting and MAR may ensure that small communities have access to a year-round sustainable water resource

5.3.4.2 Where would it be useful?

- It can be applied in built-up areas or at individual buildings with sufficiently large roof top areas

5.3.4.3 What are the advantages?

- Relatively small foot print
- Relatively low costs
- Combination of RWH and MAR
- No pumping required if constructed properly
- It can recharge groundwater at/near areas where groundwater is being depleted the (urban groundwater extraction for human consumption)
- It can be applied in areas where there is no space for ponds or infiltration channels
- In combination with a small diameter extraction well small communities have access to a sustainable source of water year-round

5.3.4.4 What are the disadvantages?

- It can only be applied in built-up areas with sufficiently large roof top areas (>3000 ft^2 / 279 m^2 as a rule of thumb (Acacia Water, 2020))
- The roof size limits the infiltration volume

5.4 Guidelines for MAR construction and performance

The UNICEF-MAR project started in 2009 with the design and testing of low cost MAR schemes for community water supply in the saline region of the coastal plain in Bangladesh (Satkhira, Khulna and Bagerhat districts in Khulna Division).

A total of 20 pilot schemes were constructed and tested in the period 2010-2014. The results and experiences were used for the first phase of upscaling under which 75 schemes were constructed by DPHE in 2014-2105. All 95 schemes were handed over to the Water User Groups by the end of 2015. In the following years, the Dhaka University team in Khulna kept recording the technical operation of these MAR systems as well as registered the experiences of the users, care taker and technical supervisor, which has resulted in a valuable set of long-term monitoring data of MAR schemes in Bangladesh. During 2014 extensive testing of the performance of test sites was carried out that resulted in improvements to the designs. The focus on the technical feasibility has resulted in a wealth of lessons learned on the siting, design, construction, O&M and monitoring of MAR schemes. These lessons learned have been reported in Technical Report no. 8 - MAR system action research (Acacia Water and Dhaka University (2015b)) and form the base for this chapter, where the lessons learned in the Coastal Plain have been translated to the context of the Barind.

5.4.1 System design and construction

5.4.1.1 Surveys and siting

Suitable locations for MAR schemes have to meet a number of physical and demographic requirements. A first selection of locations can be made based on Global Information System (GIS) based analysis. This should be followed by a site visit to check the site and involve the local community. Once the community agrees and preliminary site selection criteria (size of pond, roof, quality source water (f.e. pesticides in irrigation channels), availability of land needed for site construction and accessibility) are found favorable, the site is listed for next phase exploration towards design and constructions. This includes the drilling of 1 or 2 exploratory wells to check the thickness of the clay and the sandy aquifer underneath, the quality of the ambient groundwater underneath the clay and the groundwater level. The siting of suitable locations should be done in close cooperation with the future users (WUG) but requires expert input which cannot be provided by local Non-Government Organization (NGO)'s.

5.4.1.2 System design

Three type of designs have been described in previous chapters, each with its own characteristics and specific design. But in general, the main components of the system design are:

- Intake system from the irrigation channel (via a pond) or from the roof;
- Sand filter for pre-treatment of the water;
- Pumping and distribution system to convey water to the infiltration wells; (except for the infiltration shafts/wells in the irrigation channels, which do not require any pumping)
- Infiltration wells, the design of which depends on site specific parameters such as thickness of the clay and the thickness and grain size of the aquifer;
- Monitoring wells;
- Optionally: extraction well with platform.

Acacia Water and Dhaka University (2015a) found that infiltration through PVC pipes (casing and screens) provides much higher infiltration rates and is preferred above infiltration through gravel. The operation of the sand filters of the 20 test schemes has led to considerable improvements including the use of jute canvas to improve the cleaning process Acacia Water and Dhaka University (2015b). In order to sustain systems with higher infiltration capacities, the capacities of the sand filters and storage tank should increase as well.

Design improvement is a continuous process and should assure that the experiences of the users, care taker and technical supervisor are registered and incorporated.

Very few detailed manuals including ready-to-built MAR scheme designs exist, one exception being the MAR-CAB report (Acacia Water et al., 2021). It is acknowledged that preparing the technical design of a MAR scheme is specialist work.

5.4.1.3 Construction and supervision

As much as possible, local drillers should be motivated to drill the infiltration wells, monitoring wells and extraction well and civil works can be constructed by local contractors, under a competitive bidding process. Supervision of the works should be done by a team consisted of Hydrogeologists and Field Engineers. Local communities should be involved in the supervision process by constituting a 5 member supervision committee.

Local materials can be used for site construction with the exception of the PVC pipes and screens.

Well drilling by percussion (instead of rotary circulation) is the preferred method and should be promoted as the method to apply for future MAR schemes. Although slightly more expensive, this method requires less or no drilling mud at all and reduces the clogging risk.

Development of the infiltration wells (by airlift) and testing new schemes on the infiltration rates should be an integrated component of the construction (and supervision).

Adequate supervision is a key element to assure the quality of the work.

Maintaining quality of constructions and materials can be a major challenge during the construction of MAR sites, and requires continuous support, and control on contractors, from the supervision team. Involvement of local communities and NGOs have been found useful in facilitating constructions and maintaining work and material qualities.

5.4.2 System performance

System performance of a MAR scheme includes both the water quality and quantity aspect. Below are the lessons learned for the subsequent steps in the operation of the systems: intake and pre-treatment, infiltration, underground storage and (optionally) extraction of the water for use.

5.4.2.1 Intake and sand filter

Turbidity of the irrigation channel water and pond water is important as it determines the effectiveness of the sand filter performance. Measures to control the turbidity in the present and in future schemes are:

- More emphasis on pond protection measures;

- Pre-treatment of pond water (settling tank and/or dosing of flocculation agent);

- Reliable monitoring of the turbidity (by introducing the Secchi disk for monitoring);

- Clear guidelines on pond water turbidity, salinity and pesticide threshold values (when intake has to be suspended).

The capacity of sand filters are often found the limiting factor of a MAR scheme. In order to optimize the capacity of the sand filters, the design, operation and maintenance of the sand filter and water storage tank should be improved. This can be achieved by optimizing the pre-treatment, increasing the size of the filters and operate the filters more continuously (overnight).

5.4.2.2 Infiltration and clogging

The infiltration test and well tests carried out (Acacia Water and Dhaka University, 2015b) has resulted in the following recommendations:

- To avoid poor performance the wells should be developed after drilling and construction by air lift pumping and surging;
- Preferably wells should be drilled by percussion as this require less or no drilling mud at all;
- Conduct an infiltration test on each infiltration well and the piezometers in the infiltration well to determine the infiltration capacity of each well and the site as a whole;
- During operation infiltration tests should be repeated once a year and cleaning done on monitoring wells of which the capacity has reduced by more than 25%;
- Infiltration wells should contain just open casings and screens (no gravel wells or infiltration shafts), which enables water to enter directly into the aquifer;
- Screens should penetrate the entire aquifer or at least 10 m and be surrounded by a gravel pack;
- Infiltrated water should be the same or better quality than the water in the aquifer.

5.4.2.3 Underground storage

The storage of the infiltrated water in the aquifer is an important component of the MAR system. In case the infiltrated water needs to be abstracted again, a better knowledge of the shape of the water bubble and of the Recovery Efficiency (RE) is required. The shape of the water bubble depends a lot on soil heterogeneity (preferential flow through higher conductive parts of the aquifer) and the infiltrated water might move under influence of lateral groundwater flow might move (known as bubble drift). The RE is site specific and depends on the salinity of the ambient water, the infiltration water chemistry and the aquifer characteristics.

The residence time of the infiltrated water in the aquifer is a critical issue as it determines the bacterial degradation. A residence time of 60 days is often used a rule of thumb to assure that water in the aquifer is safe of bacteria. This time is not expected to be reached in the MAR systems where the extraction well is placed in the center of the infiltration wells at a distance of a few meters. Periodic testing of the bacteriological quality is important. High bacterial counts can be reduced by improving/reworking the sand filter.

On the other hand, most pesticides, which can be found in high concentrations in the water of the irrigation channels in agricultural areas, have an even longer residence time than 60 days.

5.4.2.4 Extraction and use

In the Barind, the sole purpose of the artificial infiltration could be to slow down the decline of groundwater levels, which have been observed in the Barind for decades. If the main purpose of the MAR scheme is additional infiltration only, the requirements of the infiltrated water quality and system performance are less strict than in case the water needs to be abstracted and used again.

Extraction and use of the infiltrated water depends on the thresholds for water quality. In the Barind, the level of pesticides in the infiltrated water could be too high for human consumption, in which case the water should not be used without treatment.

In some other locations, the salinity or arsenic concentrations in the ambient groundwater could be too high, which requires the development of a fresh water bubble.

Completed schemes are not ready for immediate use but need infiltration during at least one monsoon period to allow the fresh water bubble to develop. During this period the system has to be operated and monitored (flow and quality) continuously while there is no revenue yet from the use of the water. From the testing of the 20 pilot schemes, this incubation period appeared to be between 3 months to 3 years of infiltration. Time variation was due to the ambient water salinity in the target aquifer; quality and quantity of infiltrated water; hydraulic characteristics of the aquifer and clogging management at the filters placed at the pre-treatment tank and infiltration wells.

5.4.3 Operation, Maintenance and Monitoring

To support sustainable use of MAR a good functioning system is of high importance. In this chapter guidelines for operation, maintenance and monitoring are described, to be carried out by the suitable institution (such as Department of Public Health Engineering (DPHE)) for it to be successful. The key elements for ownership are the combination of awareness for improved (safe) water supply and leadership in the village (or at the MAR site) to manage the process of improved water supply. The key players in the OM&M performance in order to retain proper functioning of the MAR system are the Technical Supervisor and the Care Taker.

5.4.3.1 Operation

A caretaker in charge of day-to-day operation ensures that as much water as possible is infiltrated during the rainy season.

In case of a system with pond and sand filter (Paragraph 5.2), a pump needs to be switched on to fill the sand filter reservoir. It is refilled when almost all water is infiltrated. In larger or more advanced systems this task can be automated by using a floating switch that automatically turns on the pump when the water level in the sand filter reservoir drops below a certain threshold.

In case water is infiltrated under gravity directly from the irrigation channel (Paragraph 5.1), or in case water is sourced from a roof (Paragraph 5.3) there is no pump and operation is even simpler. Nevertheless, a caretaker should be present to guarantee the functioning of the system, especially during the rainy season. The caretaker ensures that all pipes are free (no debris or other clogging), that the roof is clean, and he/she monitors that the water infiltrates quickly enough (the sand on top of the infiltration unit should be cleaned regularly). The caretaker is also responsible for discarding the runoff from the first rain – this first flush usually carries too much dirt and cannot be infiltrated. As a rule of thumb, we recommend discarding the first flush of harvested rainwater after three or more days without rain.

5.4.3.2 Maintenance

Maintenance includes all necessary repairs and a number of regular maintenance tasks that ensure a reliable functioning of the MAR system. Specially to handle unforeseen problems in the day-to-day operation it is recommended that each caretaker is in contact with a technical resource person who knows the ins and outs of the system very well and who can give technical support at short notice.

Regular maintenance includes the servicing of the pumps (e.g. replace oil and oil filter in motor pump, replace plunger rubber of hand pump).

The jute canvas/mesh and the top layer of the sand filter have to be washed or replaced regularly when infiltration in the sand filter drops noticeably (e.g. less than 4 in./h). How often this needs to be done depends on the turbidity of the pond water. Once or twice per year the entire sand and gravel should be taken out of the tank for washing.

Back flushing of the infiltration wells needs to be done once a month or when the infiltration capacity of a well decreases noticeably. During Back flushing water is pumped from the infiltration wells to remove any dirt in the filter area. Back flushing can be done with a regular suction motor pump by pumping from the well at maximum pumping capacity for 15 minutes. Back flushing is detrimental for ensuring long-term functioning of the MAR system. Clogging of the infiltration wells will occur even when a well-functioning sand filter is used for pre-treatment. However, clogging can be managed and the decrease in infiltration rate can be kept at a minimum by doing regular back flushing. If back-flushing fails to bring an infiltration well back to acceptable infiltration rates (e.g. 70% of the initial infiltration rate), other well regeneration methods are available (e.g. air lifting, plunging, chemical treatment). These more advanced well regeneration methods should be carried out by an experienced driller.

Another important aspect of maintenance is to ensure good water quality of the water source by e.g. stabilizing the banks of the pond to reduce turbidity or by cleaning the roof. It is also important to make all community members aware that the pond/River/roof is used for drinking water production and that no contaminating practices (latrines, livestock watering, chemical use, etc.) should take place near the water source.

The MAR site must be protected against erosion during heavy rainfalls to prevent cracks in the concrete, damaged pipes, and settling of the tank or well heads. Surface drains must be well maintained so that rainwater can be led away from the MAR site quickly. Especially the platform of the hand pump needs to be kept in good condition.

5.4.3.3 Monitoring

Depending on the purpose and use of the MAR scheme, the water quality and quantity need to be monitored. Monitoring is important to evaluate whether the MAR system is still functioning satisfactorily. If water is abstracted for human consumption, water quality monitoring is required to guarantee that safe drinking water is produced. If any of the water quality parameters do not meet the set drinking water quality requirements the extraction needs to be stopped and the problem needs to be resolved. Regular monitoring tasks can be the responsibility of the caretaker or operator. Depending on the type of MAR, these include:

- In order to keep track of the operation of a MAR scheme, it is highly recommended to measure and record the volumes of water infiltrated, ideally combined with groundwater level monitoring in the Monitoring Well (which was the Test Well prior to construction of the MAR scheme).
- Weekly recording of infiltration (and extraction) flow meter readings can be used to check if the infiltration capacity of individual wells decreases and to monitor how much water has been infiltrated and abstracted in total.

- Infiltration rates (and extraction rates) can be measured with the installation of (a) water flow meter(s), for example in the pipe between the water tank and infiltration well(s). Readings of the flow meter should be recorded by the Care Taker, for appreciation of the Technical Supervisor.
- For further analysis of the MAR scheme it is highly recommended to monitor groundwater levels in a monitoring well at the MAR site. For this purpose, the Testing Well (drilled to determine site suitability in the reconnaissance phase) can be used for manual (or automatic) reading and recording of groundwater levels.
- Weekly recording of the infiltration rate of the sand filter (time it takes for all water to seep through the sand). This will help determine when the sand filter needs to be cleaned or replaced.
- Also record the turbidity of the water abstracted from the pond (or directly from the irrigation channel) and the outflow water after sand filtration. Turbidity of the pond water should remain below a threshold level and it needs to be checked on a daily basis. This is important to avoid clogging of the sand filter and/or clogging of the filter pack of the infiltration well(s). Based on the experiences during the research (Acacia Water and Dhaka University, 2015b), a measured turbidity of the filtered water with the turbidity tube of 10 NTU, has been given as threshold values to the site caretaker. Whenever threshold value is exceeded, infiltration should be stopped and the sand filter bed is maintained to achieve the target value.
- The bacteriological quality of the stored water is an important parameter for MAR systems designed to provide safe water for human consumption. Periodical sampling of the water for bacteriological testing (f.e. faecal coliforms) should be part of the monitoring program. The sampling rate depends on the reliability of the system and should be fairly high in the beginning.
- Regular measurements of other contaminants, such as nitrogen, pesticides, and manganese might be required as well. The sampling frequency depends on the source water quality.
- Mixing of different types of water can also lead to chemical clogging, especially in the gravel pack of infiltration (and extraction) well screens. Monitoring of iron (Fe) and manganese (Mn) concentrations in the infiltrated water (and dissolved oxygen (DO) in the ambient groundwater) are recommended.
- In many locations in Bangladesh, the salinity and arsenic concentration of the ambient groundwater is an important water quality parameter to consider. However, in the Barind issues with salinity or arsenic are not common.
- Pesticides however are expected to be present in the irrigation channel water. A monitoring programme on pesticides in both infiltrated water and abstracted water is needed in order to show whether high concentrations of pesticides do form a risk for MAR scheme operation and use.

6 MAR SUITABILITY

For MAR to be applicable, first three conditions need to be met:

First, there needs to be a demand for additional recharge of groundwater (i.e. there needs to be groundwater depletion). This condition seems to go up for the entire high Barind away from the influence of River valleys (Figure 9).

Second, the physiographical conditions need to be favorable for artificial recharge. For the Barind region, this is a challenge because of the thick clay layer at the surface. Measures to promote groundwater recharge at the surface, such as check dams, wetlands, surface water spreading are not suitable. Hence, only infiltration through shafts or wells that penetrate through the clay layer is a suitable technique. These are discussed in the previous chapter.

Third, sufficient source water needs to be available. The monsoon season is reasonably predictable, and brings sufficient source water. However, because the season is short, all water needs to be captured and infiltrated during the months with surplus water. Much of the monsoon water is captured in rice paddies that have a very low infiltration rate because of hard pans developing below the paddies. In fact, the most significant recharge from rice paddies is thorough the bunds separating the paddies (Rushton, 2016). In a way, in much of the current land use practices, loosing water to groundwater recharge is undesired, as it means that groundwater needs to be pumped up earlier. An exception are the irrigation canals, and perhaps the ponds (even though these are also often replenished with groundwater). Also, rooftops provide an easy source of water.

The three designs discussed in Chapter 5 meet these conditions, in case roof tops or irrigation canals are available. For instance, the recharge shafts and wells in irrigation channels can only be applied where irrigation channels are present. The modified type of recharge wells can be applied where irrigation channels are present, but also where ponds are present. Alternatively, they can be applied further away from irrigation canals, but that would require pipeline infrastructure. Lastly, roof top rainwater harvesting is only feasible when rooftops are available, hence in urban or industrial settings.

Hasan et al. (2022) delineated zones and sites for artificial recharge of groundwater by superimposing different background maps (Figure 22). Their suitability map contains regions with unsuitable, moderately suitable and suitable artificial recharge locations. Roughly, the highest part of the Barind is identified as unsuitable, the area around with gentle slopes as moderately suitable, and some low-lying areas as highly suitable. The measures that they propose to promote recharge are check dams in the valleys and “MAR and Percolation tank zones”. The type of MAR or the source water is however not specified.

The area that is unsuitable largely coincides with the area that has a groundwater deficit. This can be explained by the fact that recharge is indeed difficult here and naturally only occurring poorly.

Error! Reference source not found. shows a number of background maps and a MAR suitability study developed by Center for Environmental and Geographic Information Services (CEGIS). Such as surface lithology, clay thickness, transmissivity, groundwater depth after dry period, groundwater depth after monsoon, dynamics in groundwater depth, trend in groundwater depth, rainfall distribution, slope, land use and soil texture. These factors all influence the suitability for MAR.

Figure 22 Artificial recharge zone map of the Barind region. (Hasan et al., 2022)

7 MAR FEASIBILITY

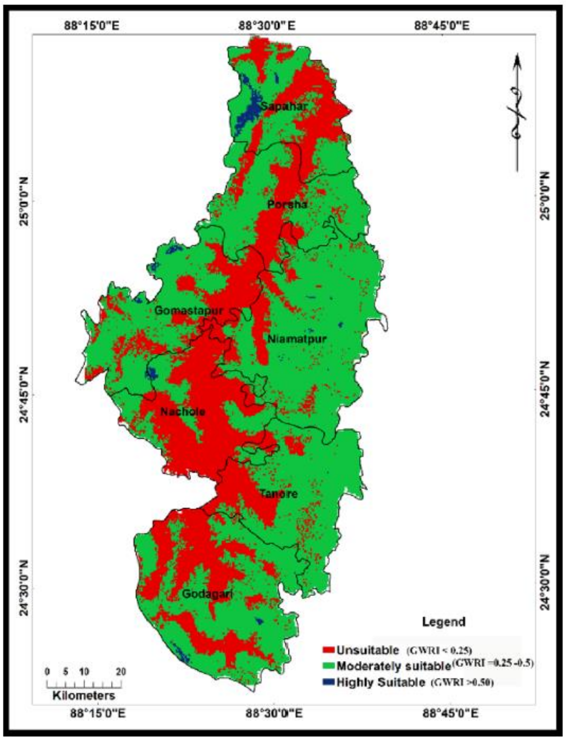
7.1 economic effect of groundwater level decrease in agricultural regions

Worldwide 70% of groundwater withdrawals are used for agricultural production (UN, 2022). Around 38% of the irrigated lands are serviced by groundwater (Siebert et al., 2013). Even though groundwater extraction for irrigation accelerated food production and socio-economic development (FAO, 2020; Shah et al., 2007), agricultural withdrawals often causes depletion of groundwater because in many cases the extraction exceeds the maximum safe yield with regards to natural recharge (UN, 2022). Continental aquifers which are decoupled from contemporary recharge, like the Barind area, are highly sensitive to groundwater depletion. These regions are highly depended on groundwater for all water demand but when abstracted the water is permanently removed and the aquifer isn't recharged anymore (Bierkens and Wada, 2019).

With the groundwater levels decreasing, communities, farmers and industries globally are facing challenges with regards to water security and economic stability. Not only the resources are depleting but costs for operating pumps and wells are rising towards levels where the costs exceed benefits.

7.2 Economic effect of groundwater level decrease in the Barind

In the Barind region in Bangladesh the groundwater level decreases rapidly. The main causes are high extraction rates



for irrigation of dry season rice and the absence of sufficient recharge of the aquifer. Due to its geological characteristics natural groundwater recharge is very limited and resources are depleting. Looking from an economic perspective the groundwater depletion is causing both direct and indirect effects to the agricultural sector.

The agricultural sector in the Barind area mainly depends on rice cultivation. Since 1985, when the BMDA started its' development work. The area developed over time from a single cropping pattern to a triple cropping pattern including irrigated Boro[1] rice in the dry season. Cultivation of Boro rice completely depends on irrigation water which is mostly supplied by groundwater resources. A smaller portion is also irrigated using surface water abstracted from the Ganges River.

The direct economic effect of decreasing groundwater levels is the rising costs for extraction, which can be expressed in two different forms:

- The first is the increasing energy costs for lifting the water from greater depth. More energy is needed to do this.
- Another more disturbing effect is the decreasing lifetime of deep tube wells. As the groundwater level decreases, at some point the depth of the wells isn't sufficient anymore and new wells have to be drilled to continue extraction. In a 'business as usual' situation the BMDA tube wells have a lifetime of 25 years. Even though there is no data available to estimate the new lifetime, we've estimated the new costs.

Deep tube well and buried pipe-system

To estimate the increasing costs, we start with the costs of the current deep tube well and buried pipe-system. In the second step the costs will be compared with the revenues which are collected from yearly farmer contributions, a cost-benefit conclusion will be the result. The third and final step is to add a different series of life times (25, 20, 15, and 10) to the calculation. The hypothesis is that the cost-benefit will decrease with the decreasing life time of the deep tube well and will become negative at some point.

In the business-as-usual situation the Barind is covered with deep tube wells where the groundwater is lifted and distributed by buried pipes to the different farmers. The costs of these systems are shared by the BMDA at a meeting at 31-03-2022 (Table 8). The BMDA works with a lifetime of 25 year for one deep Tubewell system each 30 hectares. A complete system (deep Tubewell and buried pipes) costs 2.2 Million BDT per 30 ha ($23.731,-/30 ha).

Table 8 Costs and revenue deep tube wells in Barind area– 31-03-2022 (BMDA, personal conversation)

			$
BDT/30 ha	BDT 2.2 million	Investment costs	$23.750,-
BDT/30ha/year	BDT 88.000	Fixed yearly costs	$ 950,-
BDT/30ha/year	BDT 10.000	Pumping costs (variable yearly costs)	$ 110,-
Total yearly costs/ha	**BDT 3.266**	**BMDA costs**	**$ 35,-**

[1] 'Boro rice' is the definition for rice that is cultivated in the dry season. 'Amman rice' is the rice cultivated during monsoon season. Different varieties can be cultivated.

Farmers costs/ha/year	BDT 6.669	BMDA revenue	$ 72,-

So, the yearly costs of the tube well are BDT 3.266/ha and the yearly revenue are BDT 6.669/ha. But, if the groundwater level declines the pumping costs will increase because of the higher energy demand. And there is a chance that the depth of the tube wells is not sufficient anymore and the BMDA has to reinvest before the end of the 25 years. If we perform a quick calculation with different lifetimes and more re-investment by the BMDA we see that the cost-benefit declines as the lifetime becomes shorter (Figure 23). With a lifetime of only 13 years the cost-benefit ratio turns out negative.

This calculation should be used as an indication as there are some assumptions that limit the analytical value. The calculation is based on the assumption that the investment costs of the deep tube wells, yearly pumping costs and irrigation costs paid by the farmers stay the same. This assumption is biased because costs will increase as drilling has to go deeper and more energy needs to be used because of higher lifting. But, because of the lack of data these assumptions are used.

Besides, based on this calculation we cannot make any conclusions as the team has no information about other costs BMDA makes like personnel and other overhead.

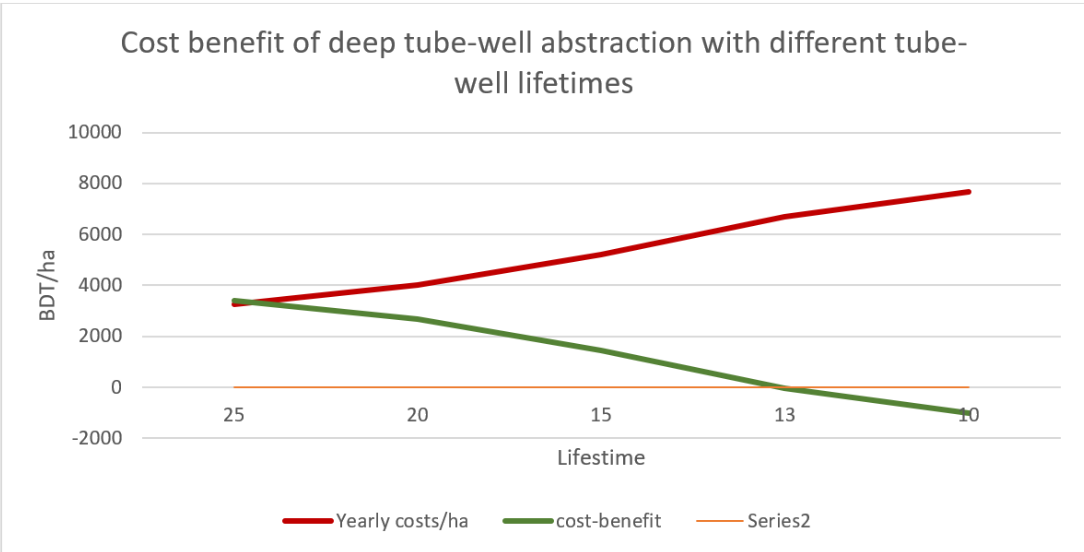


Figure 23 Cost benefit analysis of deep tubewell extraction with different tube-well lifetimes.

7.3 Solutions, costs and capacities

In the factsheets developed in this project three designs are discussed I) infiltration shafts/wells in irrigation canals II) MAR system along irrigation canal with pond and sand filter and III) rooftop water harvesting & infiltration MAR. In the last step of the analysis the team used identified the investment costs needed to make a difference in the Barind.

To do so the designs are analyzed based on their volumes, investment costs and yearly costs. The first estimation is that of the abstracted water in the high-Barind, which is 920 million m^3 per year. This amount is divided by the infiltration capacity of each system to conclude of the number of systems needed and from there the cost estimations are made. The costs are presented as $/$m^3$ which allows us to compare the different designs.

Table 9. Design assumptions on volumes and costs

System capacity	m^3/year	Investment costs	Yearly costs	Lifetime
I) Modified infiltration shafts	**4800**	**$4.000,00**	**$830,00**	**10**
IIa) MAR along irrigation canal, infiltration capacity 25 m^3/hour	**60000**	**$26.000,00**	**$2.600,00**	**10**
IIb) MAR along irrigation canal, infiltration capacity 50 m^3/hour	**120000**	**$32.000,00**	**$3.900,00**	**10**
IIc) MAR along irrigation canal, infiltration capacity 75 m^3/hour	**180000**	**$38.000,00**	**$5.200,00**	**10**
IId) MAR along irrigation canal, infiltration capacity 100 m^3/hour	**240000**	**$44.000,00**	**$6.500,00**	**10**
III) Rooftop rainwater harvesting	**283**	**$500,00**		

Table 9 shows the assumptions per system regarding the infiltration capacity in m^3/year, the investment costs, the yearly costs, and the estimated average lifetime. What stands out in the table are the four different infiltration scenarios for II, the '*MAR system along irrigation canal with pond and sand filter*'. As described in the factsheets this system can be very different in terms of infiltration capacity which influences the design and the costs. The scenarios used in the calculation (a, b, c and d) correspond to an infiltration capacity of respectively 25, 50, 75 and 100 m^3/hour and 10 wells. The limiting factor is the size of the coarse sand filter.

7.3.1 Volumes

Based on the Meta-model the estimated extraction rate is 356 mm. Multiplied by the total surface area of the high Barind considered of 2600 km^2 this translates to a total volume of 920 million m^3 abstracted groundwater for irrigation per year. Using the infiltration capacity for each of the designs we can conclude on the number of systems needed to recover the extraction. As 100% recharge (920 million m^3) might be an overestimation of what is actually possible, a range of recharge percentages is taken into account: 100%; 50%; 10% and 1% (see Table 10) of the total abstracted volume. The high volume of abstracted water in the high Barind together with the low infiltration capacity make that a high number of small-scale systems (modified infiltration shafts and rooftop rainwater harvesting) is needed to fully recover groundwater extraction. Using infiltration shafts a 100% recovery would take 192.000 systems, using rooftop rainwater harvesting would take more than 3 million systems. The MAR along the side of the irrigation canal needs in between 15.000 – 4.000 systems for full recovery. Apart from the high number of systems, the high volume would also mean that 24% of the total precipitation, or 68% of the total calculated runoff according to the meta-model needs to be infiltrated. This is quite a challenge.

Table 10. Number of systems needed to recharge 100%; 50%; 10% or 1% of 920 million m^3 in the High Barind.

	100% recharge	50% recharge	10% recharge	1% recharge
I) Modified infiltration shafts	191.667	95.833	19.167	1.917
IIa) MAR along irrigation canal, infiltration capacity 25 m^3/hour	15.333	7.667	1.533	1.53
IIb) MAR along irrigation canal, infiltration capacity 50 m^3/hour	7.667	3.833	767	77
IIc) MAR along irrigation canal, infiltration capacity 75 m^3/hour	5.111	2.556	511	51
IId) MAR along irrigation canal, infiltration capacity 100 m^3/hour	3.833	1.917	383	38
III) Rooftop rainwater harvesting	3.250.883	1.625.442	325.088	32.509

7.3.2 Investment costs and yearly costs

As presented in the different factsheets and shown in

Table 9 the investment and yearly costs are estimated per system. These costs are used to calculate the total investment and yearly costs when taken into account the number of systems needed (Table 11). Investment costs are made in year 0, we assume that the systems will last 10 years, the yearly costs (Table 12) will be calculated for this lifetime.

Table 11. Investment costs to recharge 100%; 50%; 10% or 1% of 920 million m^3 in the High Barind

	100% recharge	50% recharge	10% recharge	1% recharge
I) Modified infiltration shafts	$770.000.000	$384.000.000	$77.000.000	$7.700.000
IIa) MAR along irrigation canal, infiltration capacity 25 m^3/hour	$400.000.000	$200.000.000	$40.000.000	$4.000.000
IIb) MAR along irrigation canal, infiltration capacity 50 m^3/hour	$245.000.000	$123.000.000	$24.500.000	$2.450.000
IIc) MAR along irrigation canal, infiltration capacity 75 m^3/hour	$195.000.000	$97.000.000	$19.500.000	$1.950.000

IId) MAR along irrigation canal, infiltration capacity 100 m^3/hour	$170.000.000	$84.500.000	$17.000.000	$1.700.000
III) Rooftop rainwater harvesting	$1.625.000.000	$813.000.000	$162.500.000	$16.250.000

For the rooftop rainwater harvesting system no yearly costs are considered. These small-scale systems are mainly used within household compounds and maintained by the owners without big costs involved.

Table 12. Yearly costs to recharge 100%; 50%; 10% or 1% of 920 million m3 in the High Barind

	100% recharge	50% recharge	10% recharge	1% recharge
I) Modified infiltration shafts	$160.000.000	$80.000.000	$16.000.000	$1.600.000
IIa) MAR along irrigation canal, infiltration capacity 25 m^3/hour	$40.000.000	$20.000.000	$4.000.000	$400.000
IIb) MAR along irrigation canal, infiltration capacity 50 m^3/hour	$30.000.000	$15.000.000	$3.000.000	$300.000
IIc) MAR along irrigation canal, infiltration capacity 75 m^3/hour	$27.000.000	$13.300.000	$2.700.000	$270.000
IId) MAR along irrigation canal, infiltration capacity 100 m^3/hour	$25.000.000	$12.500.000	$2.500.000	$250.000
III) Rooftop rainwater harvesting	$0	$0	$0	$0

7.3.3 $ per m³

When we divide the total costs with the volume of recharged water over 10 years the result is a presentation of costs in $/m^3 (Table 13). Concluding, the higher the recharge capacity the more cost-efficient the system will be. The MAR irrigation canal infiltration systems will create the most effective investment per m^3 over 10 years. The most positive characteristic of the design is the high infiltration volume per system, especially when the overhead pressure is high (scenario 3 and 4). An extra benefit of these scenarios is that high overhead pressure is a natural result of groundwater depletion, which means that high infiltration capacity can be created there where depletion is high.

Even though the smaller designs are less cost-effective, these system designs are of high value to the local communities in the Barind. Rooftop rainwater harvesting and recharge on a local scale is making use of an easy design and serves those who are in danger of water shortage. The infiltration shafts can be seen as a 'no regret' design as they don't make use of any valuable land as they are located in the middle of the irrigation canals. The only important consideration is that the infiltration shafts need proper maintenance for it to stay effective over time. A drawback is that even with maintenance, they likely lose their effectiveness over time and the initial investment doesn't weigh up against the amount of water recharged over the lifetime of the recharge well.

Table 13. $/m^3 per design

No. of systems needed	$/m^3
I) Modified infiltration shafts	$0,26
IIa) MAR along irrigation canal, infiltration capacity 25 m^3/hour	$0,09
IIb) MAR along irrigation canal, infiltration capacity 50 m^3/hour	$0,06
IIc) MAR along irrigation canal, infiltration capacity 75 m^3/hour	$0,05
IId) MAR along irrigation canal, infiltration capacity 100 m^3/hour	$0,05
III) Rooftop rainwater harvesting	$0,18

8 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

Need for MAR

The groundwater monitoring wells show that below the thick clay layer, groundwater is indeed depleting. The hydrographs show that the system is close to a new balance in which extraction is met by reduced discharge of groundwater, and probably induced recharge from Rivers leading to streamflow depletion. In the areas around the high Barind, the groundwater extraction during the dry season is balanced by infiltration during the monsoon season. However, even though this is sustainable from a water supply point of view, adverse effects can be expected from the low groundwater levels during the dry season, such as groundwater contamination, loss of groundwater dependent nature and streamflow capture resulting in dry streams which inhibits other functions such as fisheries, surface water availability. MAR could be a measure replenish the groundwater and make the developed groundwater system more sustainable.

Water balance

In literature, there is a huge disparity in the different water balance terms, especially for the important terms recharge and groundwater extraction. Reasons for this is the use of different methods and different assumptions. Most importantly, the groundwater system is not taken into account which results in a comparison between “apples and oranges”. For instance the high recharge around Rivers is projected across the high Barind, which results in an overestimation of groundwater recharge values.

The water balance generated by the Bangladesh meta-model (https://jcpbd.nl/bdp-metamodel/) gives a total water balance with volumes in range of most estimates from literature. Therefore it is used for further analysis. In this water balance, the groundwater used for irrigation (356 mm) equals about 24% of the annual precipitation. Only 5% of the precipitation ends up recharging the groundwater. To make up for the abstracted groundwater, about 68% of the runoff needs to be infiltrated. This is unrealistic, and illustrates the imbalance between groundwater extraction and recharge. It stresses that alternative solutions to counter over extraction of groundwater for irrigation in the dry season are needed.

MAR designs

Three MAR designs have discussed that may be suitable for the Barind area: infiltration shafts in irrigation canals, infiltration wells along irrigation canals and rooftop rainwater harvesting. All these methods bypass the thick clay layer through wells or shafts. The disadvantage of the recharge shafts in irrigation canals is that they show progressively clogging during their life span, and they are always infiltrating which means that contaminated water can infiltrate. Infiltration wells along irrigation channels can be used when surplus water of enough quality is available. The yield is dependent on the sand filter surface area. Maintenance is easier and the well yield can be maintained for their entire life span. Rooftop water harvesting MAR needs a fairly large roof top to collect enough water.

Suitability

The suitability for MAR is dependent on 1) the demand for water, 2) the presence of favourable physiographical conditions for artificial recharge and 3) availability of source water. The demand for water is present where groundwater depletion is present. This is the case everywhere below the high Barind, away from the flood plains of the River valleys surrounding the Barind. The conditions in the high Barind are in general not suitable for artificial recharge. However, methods that bypass the clay layer such as recharge wells or shafts can be a solution. During the monsoon, plenty water is available. However, the only sources where this water can be obtained from are roof tops and irrigation canals.

Feasibility

To test to what degree MAR could be a potential solution, three MAR designs are discussed and costs and yield are estimated. The calculations show that the costs of recharging one cubic meter of water range from $0.26 to $0.05. These costs are additional to the current groundwater extraction costs, but are an investment to sustain groundwater resources for future generations.

The number of installations to significantly balance the water extraction, as derived from the metamodel, is enormous. However, considering that BMDA has installed about 16,000 DTW's in the Barind, it is not impossible. To balance 50% of the estimated withdrawals, it 2000 systems of the most efficient type would be needed. The involved investment is estimated to be over 80 million dollar and yearly costs would amount to 12 million dollar. It would mean that every kilometre of irrigation canal has a recharge installation. However, it should be realized that this is based on the metamodel water balance, and a better understanding of the water balance may result in more accurate numbers.

The costs for rooftop rainwater harvesting installations are relatively high compared to the infiltrated water volume, but can be an important solution to create a sustainable freshwater source for villages which have lost their source of fresh water due to the over extractions. This measure should not be seen as a measure to restore the groundwater balance, also because the total area of roof surface with suitable surface is too low in the agricultural Barind.

The location of the recharge wells in or near irrigation canals does have potential implications. The canals already infiltrate water during a large part of the year, and it could well be that therefore the groundwater level around the canals is relatively less depleted than further away from the canals. Applying the recharge at the place with highest depletion would mean that infiltration should happen in or near the extraction wells. This would require an extensive network of pipelines to the wells that are situated away from the canals. In addition, the lifetime of the infiltration wells can be jeopardized if clogging occurs due to water quality issues or turbid water. Still, this option of infiltrating away from the source water and relatively close to DTWs could be interesting, but is not investigated here. The costs would be similar to the infiltration well fields along an irrigation canal, but then including the transport network towards the wells.

In this study we only looked at the costs associated with MAR and the percentage of groundwater extraction that could be replenished. However, it should be realized that the groundwater balance can be restored in different ways, both on the demand side and on the supply side. For instance, surface water irrigation is already happening in the Barind, and an area of at least 50 km^2 is irrigated with water pumped up from the Padma River. Similarly, water could be pumped up from the Atrai River and Mahananda River to relieve the groundwater stress. Also, crop change and more efficient irrigation could reduce groundwater extraction volumes and improve the water balance. The costs of these measures should be compared to the costs presented in this study.

Benefits and avoided costs are difficult to establish but are an important factor for the weighing of potential measures. To better quantify the benefits and avoided costs, an in-depth groundwater resource assessment modelling study of the Barind should be executed that proceeds where this study stops. In the follow up, system knowledge should be properly incorporated. This way the discharge to the surrounding Rivers can be estimated, and also streamflow depletion from over extraction. For such a study to be possible, data sharing is key. During this study it turned out that this remains a challenge, and it impedes a proper analyses.

Groundwater depletion is observed in hydrographs in the high Barind. The negative effects are already observed, and likely the costs of pumping may be exceeding the benefits soon, as a result of shorter well life, higher lifting costs and deeper drilling. Hence, this situation is not sustainable. MAR could have a role in making the situation more sustainable, but proves to be a big challenge. Small scale systems such as Design #3 can relieve local groundwater stress and promote sustainable groundwater use in communities. Larger scale systems can most easily be applied at locations where source water is available during the monsoon season. These are the irrigation canals and roof tops. Only the irrigation canals carry enough water to potentially partially balance the groundwater over extraction, and therefore along these canals would be the most feasible recharge potential. Design #2 seems the most cost-effective method over time. In this design a small pond is fed from the irrigation canal when surplus water is available. From this pond, the water is pumped through a sand filter unit and injected through several infiltration wells. Design #1, the original design of infiltration shafts in the irrigation canals, shows gradually diminishing yield over time due to clogging, also after maintenance. This results in a short productive life time, and therefore high costs per infiltrated cubic meter of water over the long term.

The most optimal design would cost $0.05 of water infiltrated. The number of installations to significantly balance the water extraction is about 4000 systems, costing over 400 million dollars for the first 10 years. However, considering that BMDA has installed about 16,000 DTW's in the Barind, it is not impossible. To balance 50% of the estimated withdrawals, 2000 systems of the most efficient type would be needed. The involved investment is estimated to be over 80 million dollar and yearly costs would amount to 12 million dollar. In practice, this would mean that every kilometre of irrigation canal would have a MAR installation with 10 infiltration wells. An issue may be that because irrigation canals are slowly infiltrating water already, these locations are probably not the locations with the highest groundwater depletion.

All in all, MAR in the Barind region is likely a difficult story. The results from this feasibility study can be compared to the costs involved with other measures such as crop change, pumping up surface water from surrounding Rivers or other IWRM measures.

The recommendations from this study are as follows:

Water balance / groundwater system:

- It is important to improve the estimates of the different terms of the water balance. With the current estimates from literature, it is impossible to determine the sustainability of extraction and the amount of water needed to balance the system. It would be good to have an independent study to confirm of disprove the water balance of the metamodel that this study is based on.
- For the reporting of quantities of terms of the water balance, such as extraction or recharge, make a distinction between the high Barind where groundwater depletion takes place, and the low-lying areas where the groundwater table recovers during monsoon
- The groundwater system analysis would benefit from better data sharing.
- A consistent mapping campaign would largely improve the groundwater system understanding. One of the important questions is whether the sandy River channel belts are in contact with the aquifer, or underlain by the Barind clay. Furthermore infiltration test should be performed across the entire Barind.

MAR designs:

- In this report we have used state-of-the-art knowledge to draw up MAR designs that could work in the challenging setting of the Barind. However, a closer look at the cost estimates and materials may result in lower cost estimates and more cost-effective designs. For instance production of components by local industries could reduce costs
- Design #2 is now sited right along the irrigation canals. It would be interesting to see whether these designs can be implemented next to the extraction wells. This way the water is recharged at the location where the largest drawdowns take place. For this, additional infrastructure (pipelines, canals) needs to be put in place.

MAR feasibility:

- This study provides an estimate of the costs involved for MAR in the Barind to move to a more sustainable water balance. The costs reported in this study should be compared to other IWRM measures to decide on the most effective set of measures.

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