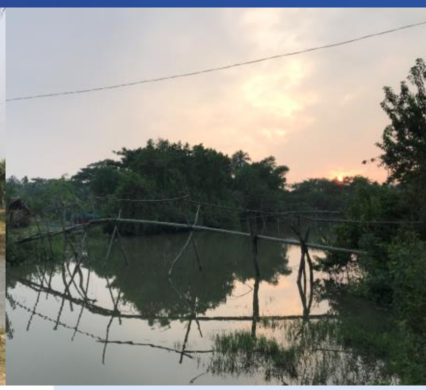
Jan 31, 2019

Technical report AgriMAR

Agricultural Managed Aquifer Recharge to provide irrigation water for saline agriculture in Bagerhat District, Bangladesh

Final report



ACACIA WATER

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1 Introduction

In the period of December 2018 and January 2019, a managed aquifer recharge (MAR) system for irrigation of crops with different salt tolerance levels was constructed in the district of Bagerhat, in the coastal plain south of Khulna, Bangladesh. Direct client is Salt Farm Texel, who is setting up a test site for salt tolerant crops. The project is funded by ICCO, the donor agency which is looking into the potential of off-season irrigated farming on a larger scale in the coastal plain.

In 2011, UNICEF with the support of Dhaka University and Acacia Water introduced small MAR schemes for the rural water supply in Bangladesh. At present, 95 of these MAR schemes have been constructed and technically the schemes function well. Based on the success of the UNICEF MAR schemes, Salt Farm Texel asked Acacia Water to make a design for a MAR scheme for irrigated farming (AgriMAR).

In the beginning of 2018, a feasibility study including exploration drilling and field visit was done by Acacia Water on two agricultural research stations in Khulna region: the BARI station (Bangladesh Agricultural Research Institute) at Sathkira, and the SRDI station (Soil Resources Development Institute) at Baghiata. Halfway 2018 it turned out that the AgriMAR project could not be continued at both the BARI and the SRDI site. Therefore, a new site was selected by Salt Farm Texel, located in the administrative region (*upazila*) of Rampal, district (*zila*) of Bagerhat. Exploration drillings were performed on this site in the end of October 2018, and early November 2018 a field visit was done by Acacia Water. Based on the outcomes of the exploration drillings and field visit, a final design and timeframe for the different construction activities for the AgriMAR system was made. In December 2018 construction works of the AgriMAR started under supervision of Acacia Water. Construction and testing of the AgriMAR system continued in January 2019 and were finalized on the 24th of January 2019.

This report starts with a hydrological background on MAR in Bangladesh (chapter 2), followed by a brief description of the feasibility studies done at the initial sites of BARI and SRDI (chapters 3), and a description of the location and site characteristics of the final site in Bagerhat (chapter 4). The results of the feasibility study for AgriMAR on this site is presented in chapter 5, and the site layout and technical design of the AgriMAR system in chapter 6. Chapter 7 describes the testing and monitoring activities of the AgriMAR system and in chapter 8 upscaling possibilities are discussed.

2 Hydrological background on Managed Aquifer Recharge systems in Bangladesh

Agriculture in the coastal belt of Bangladesh is under stress because of the increasing salinization and severe irrigation water scarcity during the dry season. To adapt on these conditions, Salt Farm Texel together with ICCO works on the introduction of salt tolerant crops to expand agricultural yield. The growth of salt tolerant crops is still influenced by the salinity level of the irrigation water. As the salinity level in the coastal rivers fluctuate strongly throughout the year, (see Figure 1) fresh irrigation water is needed to mix the water up to the preferred concentration. At the same time the agricultural sector would benefit strongly of extra irrigation water availability during the dry season.

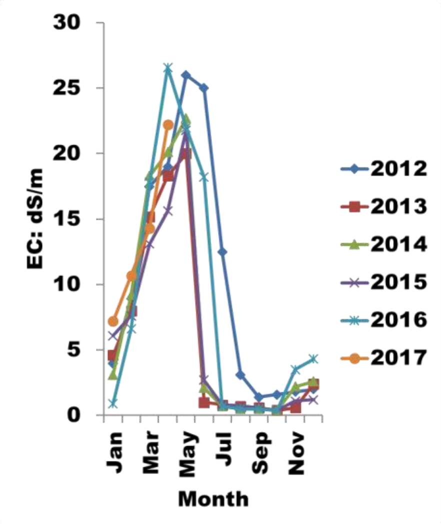


Figure 1. EC values in the Betna River, Satkhira, nearby the BARI pilot site. From January to August the water is not suitable for irrigation (source: Fakir, O.A. 2018, BARI, Stakhira)

For this purpose Acacia Water was asked to explore the possibilities of the Managed Aquifer Recharge technique. With this technique freshwater which becomes available during the monsoon is stored underground for later use in the dry season. The technique is already successfully implemented in the coastal belt for drinking water use. Application of the system for agriculture asks for the same expertise, but in different circumstances.

Acacia Water works closely together with their partner Dhaka University, who together introduced the MAR technique in 2009. Up to this moment about 95 MAR sites have been realized for village water supply funded by UNICEF. In the Netherlands Acacia Water has acquired experience with the so called AgriMAR systems. Acacia Water asked Dhaka University to cooperate in this project as well to supervise the ground truthing, exploration drillings, logistics, construction, design and monitoring. Acacia Water has also been commissioned to investigate the potential for upscaling MAR based irrigation in Bangladesh under various conditions.

In 2011 UNICEF with the support of Dhaka University and Acacia Water introduced small MAR schemes for the rural water supply. At present 95 of these schemes have been constructed. A typical scheme consists of four to six injection wells spaced at three meters from a central abstraction well operated by a hand pump. During and after the monsoon freshwater from ponds and rooftops is injected into shallow brackish aquifers via the infiltration wells. The source water is filtered and stored in an overhead tank from where it is led under gravity into the injection wells. During the rest of the year water is recovered from the freshwater bubble in the aquifer. Technically the schemes function well. Over-infiltration is necessary to avoid the breakthrough of brackish groundwater from the mixing zone around the bubble. The average recovery efficiency is 33%. So yearly water injection is about three times the recovery.

In the coastal plain of Bangladesh, the host aquifer generally has a thickness varying from 10 to 30 m and is covered by a confining clay layer with a thickness varying from a few meters to 30 m. The groundwater salinities expressed in electrical conductivities vary from 1 to 20 mS/cm. Practical experience learns that aquifers with salinities above 15 mS/cm are not suitable for MAR because of the buoyancy effect. In general, 10 m of screens are placed in the wells which is also the minimum aquifer thickness.

The AgriMAR system was designed with objective of being low-cost and low-maintenance, constructed using local materials, mostly unskilled labour and involving the local community. The scheme will function as a source of irrigation water for test plots where the water will be used either directly or after mixing water with locally available brackish water.

3 Feasibility study BARI and SRDI site

A feasibility study including exploration drilling and field visit was done by Acacia Water in the beginning of 2018 for two agricultural research stations in Khulna Division: the BARI (Bangladesh Agricultural Research Institute) station at Sathkira, and the SRDI (Soil Resources Development Institute) station at Baghiata.

3.1 BARI site

On the 4th of March 2018, the Dhaka University Team in Khulna supervised an exploration drilling at the BARI site, Satkhira (figure 2). The drilling was performed at the southern part of the test site. The lithology of the drilling showed a very thick layer of clay of 95 feet (29 m). Under the clay layer, sand is present, which is the target layer for the MAR system. For MAR implementation a thinner layer of clay is preferred, even though, it would be a possibility to drill up to 130 feet (40 m). By drilling deeper the investment costs will increase.

After a discussions and a visit of the Acacia Water team together with the Dhaka University team, the decision was made to drill another exploration drilling at the 11th of March. The drilling was performed more to the north (figure 2), as this location was expected to be more convenient for MAR implementation. A MAR site in the more elevated northern part of the BARI station will result in the most efficient situation, as from here water can reach the experimental sites by gravity, saving pumping devices and fuel. The second exploration drilling did not show a thinner clay layer as expected by experience of the local driller. The drilling showed the same clay layer of 95 feet (29 m) as the drilling in the south.

The salinity of the groundwater found during the first drilling was quite low. With an EC of 0.95 mS/cm it could be questioned if installation of a MAR to ensure fresh water is necessary. However, an arsenic concentration of 0.2 mg/l was found, which exceeds four times the permissible limit of 0.05 mg/l (WHO standard).

The BARI site seems to be in continuous state of activity and has the needed man power to operate the MAR system properly with the necessary infiltration during monsoon. The strong focus on crop research from BARI supports this as a preferred site for an AgriMAR system. As the groundwater doesn't have a very high salinity a simple well might seem enough for irrigation. But, as the water contains high arsenic concentrations, it needs to be considered whether irrigation with arsenic water needs to be avoided as it may be taken up by the crops. Our experience with the UNICEF MAR sites learns that arsenic concentrations can be lowered by storage of fresh water which avoids probable arsenic contamination within the crops.

Figure 2. Location of the Bangladesh Agricultural Research Institute (BARI) at Sathkira (left) with a photo of the first exploration drilling (right up) and the second exploration drilling (right down).

3.2 SRDI site

The SRDI (Soil Resources Development Institute) site at Baghiata, has already been explored in 2010 by the team of Dhaka University. Two lithological logs of exploration drillings are shown in figure 3. This site has suitable lithology for the implementation of MAR as there is a clay layer up to 25 feet (8 m), with a fine sandy layer of 25 feet (8 m) thickness below, which is closed at the bottom with a clay layer again. The deeper located medium to fine sand layer between 80 and >150 feet (24 and >46 m), could also be considered for MAR, even though by drilling deeper the investment costs will increase. The salinity of groundwater in the sand layer, expressed in electrical conductivity, is 3.5 mS/cm, indicating brackish conditions. The SRDI site has a suitable lithology and high potential salinity of groundwater for implementation of MAR.

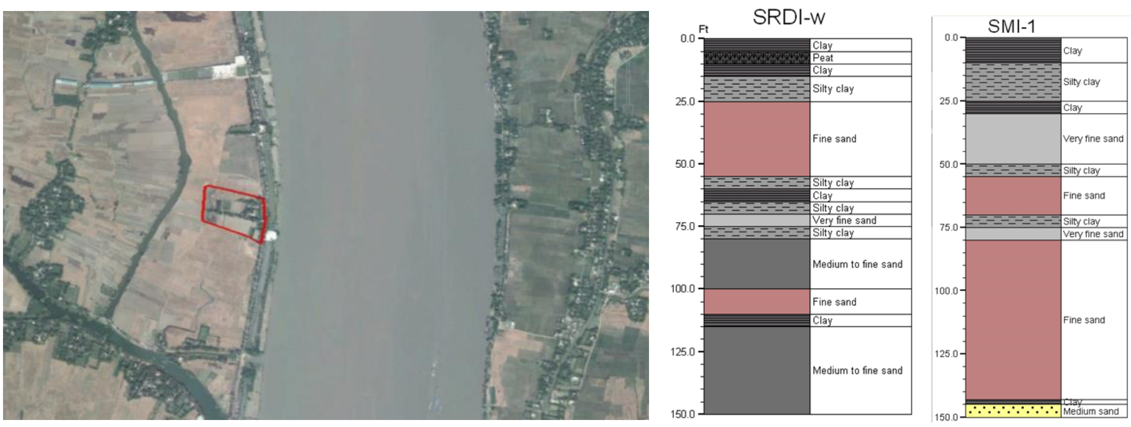


Figure 3. Location of Soil Resources Development Institute (SRDI) station at Baghiata (left) with the lithological log of the two boreholes drilled on site (right).

4 Location and site characteristics AgriMAR site Bagerhat District

4.1 Location

The new site for the AgriMAR system is located in Union/ward: 151 no. Sonnashi, Thana/upazila: Rampal, District/zila: Bagerhat in the Division of Khulna, Bangladesh. The site is located 35 km southeast of Khulna city (ca. 2.5 hour drive by car). The delineation of the site, the location and the GPS coordinates are given in the map below:

Figure 4. Location of the new AgriMAR site in Bagerhat District, located southeast of Khulna (above) and delineation of the site with the location of the three ponds just north of the river (below).

4.2 Site characterization

Based on the thematic maps made for the UNICEF MAR project (Acacia, 2014), which are added in Annex 1, the new site can be characterized as follows:

- The salinity of the shallow groundwater = saline (closely located to brackish zone)
- Main type of land-use = rice farming (closely located to fish/shrimp farming)
- Demand prioritization for MAR upscaling, based on population density and the number of existing shallow and deep tube wells = priority zone
- Technical potential for upscaling of MAR systems based on salinity of the shallow groundwater = medium potential (closely located to high potential zone) relatively high salinity of the groundwater affect the site suitability

Arsenic concentrations of the groundwater can be high in the sedimentary deposits of Bangladesh and are a potential health concern. No measurements of arsenic have been done close to the AgriMAR site (Acacia 2014), but the measurements in surrounding areas indicate that arsenic concentration in the groundwater is likely low (0 – 10 µg/l). For comparison, the WHO standard for arsenic is 10 µg/l and the Bangladesh standard is 50 µg/l.

No measurements of clay thickness or pumping tests to determine the hydraulic aquifer properties were carried out close to the AgriMAR site during the UNICEF MAR project (Acacia 2014).

5 Results feasibility study

5.1 Exploration drillings

On the 23rd and 24th of October 2018, a drilling team under supervision of Dhaka University drilled two exploration boreholes with a depth of 210 feet (64 m) and 220 feet (67 m). In the northern exploration borehole (RAF 1), a piezometer (screen depth 170-180 feet; 52 – 55 m) was installed in the deep (2nd) aquifer. In the southern exploration borehole (RAF 2), a piezometer (screen depth 90-100 feet; 27,5 – 30,5 m) was installed in the shallow (1st) aquifer. The location of the two exploration drillings and the measured Electrical Conductivity (EC) is shown in Figure 5.

On the next two pages, the results of the exploration drillings are presented. Measurements of the water quality were also done by the drilling team.

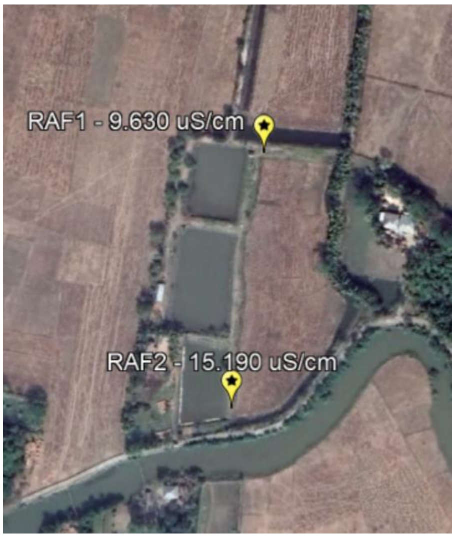


Figure 5. Location and measured EC in the northern (RAF1) and southern (RAF2) exploration drilling

5.1.1 RAF 1

Test boring log			
Site ID	RAF 1	Source type	TW
Well ID	TD 1	Total Depth (ft)	210
Date	23.10.2018	Screen Depth (ft)	170-180
District	Bagerhat	Top Clay Thickness (ft)	20
Upazila	Rampal	Aquifer Thickness (ft)	20-90 & 140-190
Pouroshova		EC (mS/cm)	9.63
Village	Boro Sannayashi	pH (mS/cm)	6.98
Ward	8	As (mg/l)	0.01
Mouza	Sannayashi	Water level (m bgl)	0.68
Site Name	Rampal Agri Farm		
Lattitude	22.56710699		
Longitude	89.73062812		

Lithologic Description

Depth from (m)	Depth to (m)	Depth from (ft)	Depth to (ft)	Lithology	Description
0.0	1.5	0	5	Clay	Bluish gray silty clay
1.5	3.0	5	10	Clay	Bluish gray silty clay
3.0	4.6	10	15	Clay	Bluish gray silty clay
4.6	6.1	15	20	Clay	Bluish gray clayey silt
6.1	7.6	20	25	Sand	Bluish gray very fine sand
7.6	9.1	25	30	Sand	Bluish gray very fine sand
9.1	10.7	30	35	Sand	Bluish gray very fine sand
10.7	12.2	35	40	Sand	Bluish gray very fine to fine sand
12.2	13.7	40	45	Sand	Bluish gray very fine to fine sand
13.7	15.2	45	50	Sand	Bluish gray very fine to fine sand
15.2	16.8	50	55	Sand	Bluish gray very fine to fine sand
16.8	18.3	55	60	Sand	Bluish gray fine sand
18.3	19.8	60	65	Sand	Bluish gray fine sand
19.8	21.3	65	70	Sand	Bluish gray fine sand
21.3	22.9	70	75	Sand	Bluish gray fine sand
22.9	24.4	75	80	Sand	Bluish gray fine sand
24.4	25.9	80	85	Sand	Bluish gray fine sand
25.9	27.4	85	90	Sand	Bluish gray very fine to fine sand
27.4	29.0	90	95	Clay	Bluish gray clayey silt with very fine sand
29.0	30.5	95	100	Clay	Bluish gray silty clay
30.5	32.0	100	105	Clay	Bluish gray silty clay
32.0	33.5	105	110	Clay	Bluish gray clayey silt with very fine sand
33.5	35.1	110	115	Clay	Bluish gray silty clay
35.1	36.6	115	120	Clay	Bluish gray silty clay
36.6	38.1	120	125	Clay	Bluish gray silty clay
38.1	39.6	125	130	Clay	Bluish gray silty clay
39.6	41.1	130	135	Clay	Bluish gray silty clay
41.1	42.7	135	140	Clay	Bluish gray silty clay
42.7	44.2	140	145	Sand	Bluish gray very fine to fine sand
44.2	45.7	145	150	Sand	Gray very fine to fine sand
45.7	47.2	150	155	Sand	Gray very fine to fine sand
47.2	48.8	155	160	Sand	Gray very fine to fine sand
48.8	50.3	160	165	Sand	Gray very fine to fine sand
50.3	51.8	165	170	Sand	Gray very fine to fine sand
51.8	53.3	170	175	Sand	Gray very fine to fine sand
53.3	54.9	175	180	Sand	Gray very fine to fine sand with organic material
54.9	56.4	180	185	Sand	Gray very fine to fine sand
56.4	57.9	185	190	Sand	Gray very fine to fine sand
57.9	59.4	190	195	Clay	Bluish gray silty clay organic material
59.4	61.0	195	200	Clay	Bluish gray silty clay with wood fragment
61.0	62.5	200	205	Clay	Bluish gray silty clay organic material
62.5	64.0	205	210	Clay	Bluish gray clayey silt with few very fine sand & organic material

5.1.2 RAF 2

Test boring log			
Site ID	**RAF 2**	**Source type**	TW
Well ID	**TD 2**	**Total Depth (ft)**	220
Date	24.10.2018	**Screen Depth (ft)**	90-100
District	Bagerhat	**Top Clay Thickness (ft)**	20
Upazila	Rampal	**Aquifer Thickness (ft)**	20-100 & 135-185
Pouroshova		**EC (mS/cm)**	15.19
Village	Boro Sannayashi	**pH (mS/cm)**	6.62
Ward	8	**As (mg/l)**	0.01
Mouza	Sannayashi	**Water level (m bgl)**	0.54
Site Name	Rampal Agri Farm		
Lattitude	22.56573972		
Longitude	89.73044273		

Lithologic Description

Depth from (m)	Depth to (m)	Depth from (ft)	Depth to (ft)	Lithology	Description
0.0	**1.5**	0	5	Clay	Bluish gray silty clay
1.5	**3.0**	5	10	Clay	Bluish gray silty clay
3.0	**4.6**	10	15	Clay	Bluish gray clayey silt
4.6	**6.1**	15	20	Clay	Bluish gray silty clay
6.1	**7.6**	20	25	Sand	Gray very fine to fine sand
7.6	**9.1**	25	30	Sand	Gray very fine to fine sand
9.1	**10.7**	30	35	Sand	Gray very fine to fine sand
10.7	**12.2**	35	40	Sand	Gray very fine to fine sand
12.2	**13.7**	40	45	Sand	Gray very fine to fine sand
13.7	**15.2**	45	50	Sand	Gray very fine to fine sand
15.2	**16.8**	50	55	Sand	Gray very fine to fine sand
16.8	**18.3**	55	60	Sand	Gray very fine to fine sand
18.3	**19.8**	60	65	Sand	Gray very fine to fine sand
19.8	**21.3**	65	70	Sand	Gray very fine to fine sand
21.3	**22.9**	70	75	Sand	Gray very fine to fine sand
22.9	**24.4**	75	80	Sand	Gray very fine to fine sand
24.4	**25.9**	80	85	Sand	Gray very fine to fine sand
25.9	**27.4**	85	90	Sand	Gray very fine to fine sand
27.4	**29.0**	90	95	Sand	Gray very fine to fine sand
29.0	**30.5**	95	100	Sand	Gray very fine to fine sand
30.5	**31.7**	100	104	Sand	Gray very fine sand
31.7	**33.5**	104	110	Clay	Bluish gray clayey silt with very fine sand
33.5	**35.1**	110	115	Clay	Bluish gray clayey silt with very fine sand
35.1	**36.6**	115	120	Clay	Bluish gray silty clay with wood fragment
36.6	**38.1**	120	125	Clay	Bluish gray silty clay with wood fragment
38.1	**39.6**	125	130	Clay	Bluish gray silty clay
39.6	**41.1**	130	135	Clay	Bluish gray silty clay
41.1	**42.7**	135	140	Sand	Bluish gray very fine sand
42.7	**44.2**	140	145	Sand	Bluish gray very fine sand
44.2	**45.7**	145	150	Sand	Gray very fine to fine sand
45.7	**47.2**	150	155	Sand	Gray very fine to fine sand
47.2	**48.8**	155	160	Sand	Gray very fine to fine sand
48.8	**50.3**	160	165	Sand	Gray very fine to fine sand
50.3	**51.8**	165	170	Sand	Gray very fine to fine sand
51.8	**53.3**	170	175	Sand	Gray very fine to fine sand
53.3	**54.9**	175	180	Sand	Gray very fine to fine sand
54.9	**56.4**	180	185	Sand	Gray very fine to fine sand
56.4	**57.9**	185	190	Clay	Bluish gray clayey silt with organic material
57.9	**59.4**	190	195	Clay	Bluish gray clayey silt with organic material
59.4	**61.0**	195	200	Sand	Bluish gray very fine to fine sand
61.0	**62.5**	200	205	Sand	Bluish gray very fine to fine sand
62.5	**64.0**	205	210	Sand	Bluish gray very fine to fine sand
64.0	**65.5**	210	215	Sand	Bluish gray very fine sand
65.5	**67.1**	215	220	Sand	Bluish gray very fine sand

5.1.3 Water quality

After the exploration drillings were completed, the drilling team measured the Electrical Conductivity of the water in several ponds, canals, shallow tube wells (STW) and deep tube wells (DTW) surrounding the AgriMAR site. The measurements, performed on October 16th and October 23rd of 2018 are presented in the table below:

Table 1. Coordinates of water points at and around the AgriMAR site and Electrical Conductivity measured in October 2018.

Sl. No.	*Date*	*Latitude*	*Longitude*	*Source type*	*Estimated depth (ft)*	*EC (mS/cm)*
1	16.10.2018	22.56560802	89.72892545	STW	40	6.97
2	16.10.2018	22.56562182	89.72871759	STW	50	8.15
3	16.10.2018	22.56692966	89.73138062	STW	38	6.77
4	16.10.2018	22.56625051	89.73191389	STW	100	4.54
5	23.10.2014	22.56909754	89.72506945	DTW	790	3.61
6	23.10.2018	22.56680278	89.73027780	Pond	6	2.76
7	23.10.2018	22.56622778	89.73027778	Pond	6	2.87
8	23.10.2018	22.56574167	89.73027778	Pond	6	2.84
9	23.10.2018	22.56717918	89.73055871	Small canal, surrounding the rice field	3	3.74
10	16.10.2018	22.56638889	89.73138889	Pond	5	1.81
11	16.10.2018	22.56721389	89.73055556	Canal	8	1.35
12	16.10.2018	22.55896389	89.71833332	DTW	900	4.03

It should be noted that the depth of the STW/DTW could not be measured but is rather an estimation according to the owner of the well.

The maps below show the measurements of the EC (in µS/cm) in ponds and canals (red), in shallow tube wells (light blue), in deep tube wells (dark blue) as well as the EC of the groundwater measured in the exploration wells (yellow), after flushing the well extensively.

Figure 6. EC measurements at and around the AgriMAR site in October 2018.

5.2 Reconnaissance visit

A reconnaissance visit of the new site and surrounding areas was performed by Acacia Water experts Harmen van den Berg MSc., and Tine te Winkel MSc., between the 4th and 7th of November 2018.

5.2.1 River/dam

- The inflow/outflow of the river south of the site is regulated by means of a dam/lock.
- During monsoon the gate are opened, after monsoon they are closed to prevent saline seawater from mixing with the freshwater in the canal system.
- It also works as a dyke (flood protection): during high water the lock is closed.
- The water authority is in charge of the dam; they open/close it depending on the users (farmers, prawn agriculture etc)
- During a visit on November 5th 2018, the dam was closed to avoid flooding of the rice fields adjacent to the river.
- The coordinates of the new lock are Lat: 22.560459° / Lon: 89.718941°

Figure 7. Photo of the new lock (left) and the old lock (right) controlling the inflow/outflow of the water in the river directly south of the site.

5.2.2 Characteristics new site

- The site is nearly flat, with a low-lying rice paddy surrounded by an elevated ridge (+1 m) of 5-10 m wide.
- The three ponds have slightly turbid water (are used for fish breeding)
- The water in the pond is a mix of rainwater and river water (which is let in during and after the rainy season (monsoon)
- Water in rice fields is rainwater, no irrigation with groundwater or surface water
- In dry season the rice field dries up. There is one rice harvest per year
  There is a shallow tube well + handpump on site, but it is not working.

Figure 8. Photo of the non-functional shallow tube well (left) and of the elevated ridge between the ponds and the rice paddy (right).

5.2.3 Water quality

On the 5th of November 2018, a water point inventory was performed by Acacia Water, during which Electrical Conductivity and Turbidity were measured using calibrated instruments. Where possible groundwater levels (GWS) were measured and other relevant observations done. The groundwater in the two exploration boreholes were flushed 100x, 200x, 300x and 400x after which the water quality measurements were repeated.

Table 2. Water point inventory at and around the AgriMAR site, including measurements of Electrical Conductivity and turbidity, measured in November 2018.

Water Point Inventory	Type	Coordinate	Coordinate	Flushing before sampling	EC	Turbidity	GWS	GWS	BH depth	Observations
		latitude	longitude	(# of pumping)	uS/cm	NTU	m-bgl	m-top tube	m-bgl	
RAF 2	**STW**	22.56573	89.73044	100x	13860	240	0.39	0.53		Top piezometer 14 cm above groundlevel
				200x	14600	200				
				300x	15200	220				
				400x	15500	190	0.43			After removing the pump
RAF 1	**STW**	22.56713	89.73059	1x	9940	30	0.60	0.67		Top piezometer 7 cm above groundlevel
				100x	9880	5				
				200x	9800	50				
				300x	9740	48				
				400x	9740	82				
Pond 1	**SW**	22.56715	89.73052		3380	100				Pond far away from river (north)
Pond 2	**SW**	22.56618	89.73008		2710	93				Central pond
Pond 3	**SW**	22.56571	89.73041		2333	40				Pond close to river (south)
Small canal surrounding rice field	**SW**	22.56721	89.73054		4690	23				
River	**SW**	22.56615	89.73118		1614	70				Dam is closed
Shallow well 1	**STW**	22.56698	89.73135		6870	<5			12.2	Not used for drinking; iron precipitation on the BH slab and handpump (high iron content) - brownish/reddish colour of the water; but clear
Pond next to STW1	**SW**	22.56697	89.73131		2210	70				Mixed rainwater and canal water (connected with river through duiker under the road)
Shallow well 2	**STW**				4570	40			50.3	
Shallow well 3	**STW**	22.56561	89.72891		7280	9			9.1	Brownish
Shallow well 4	**STW**	22.56560	89.72873		8400	<5			15.2	
Deep well 1	**DTW**	22.56914	89.72504		3790	<5			240.0	

Figure 9. EC measurements at and around the AgriMAR site in November 2018.

It should be noted that the turbidity of the groundwater in the exploration boreholes was found to be relatively high (around 50 NTU in RAF 1, around 200 NTU in RAF 2). The turbidity of the groundwater did not improve significantly after repeated flushing of the borehole (up to 400x), indicating that remaining 'dirty water' from the borehole drilling process is likely not the cause. It is thought that the turbidity of the groundwater is caused by the influx of fine particles from the clay layers that are present above and below the aquifer in which the filter screen is installed. This inflow of fine material is avoided in common good borehole drilling practise by installing a clay seal in the borehole at the outer borders of the aquifer during construction of the observation tube. During the exploration drilling and piezometer installation ('quick and cheap') this good practise was not applied, causing the water pumped from the borehole being slightly turbid. A clay seal was applied during the construction of the MAR infiltration and abstraction well.

The turbidity of the groundwater measured in shallow and deep tube wells in the surrounding area is generally low (<5 NTU). The turbidity of the water in ponds and canals is generally much higher (20 – 100 NTU).

The Electrical Conductivity (EC) of the groundwater in the exploration wells is significantly higher than the EC values measured in both shallow and deep tube wells in the surrounding area. There can be several reasons for this, but it is clear that the salinity of the shallow and deep groundwater can be very heterogeneous, it can change from place to place. Compared to the EC measurements of October 2018 (Table 1 and Figure 6), the salinity of the surface water and shallow groundwater has slightly increased in November, as expected in the course of the dry season. Exceptions are the central and southern ponds that have lower EC in November, likely due to inflow of some river water which is relatively fresh (measured at 1614 µS/cm on November 5th).

Figure 10. Photo of the flushing of exploration well RAF 1 (left) and RAF 2 (right) using a small manual handpump

Arsenic

The arsenic concentration of the groundwater in the two exploration boreholes was measured on October 24th 2018 by the Dhaka University team as being <0.01 mg/l However, it was noticed that some of the reagents of the arsenic test kit were expired, making the reliability of the arsenic measurements uncertain. In December 2018, the measurements were repeated using a new arsenic test kit. These repeated measurements confirmed that arsenic concentration in the groundwater on the AgriMAR site is lower than 0.01 mg/l.

Iron

The relatively high concentrations of (dissolved) iron in groundwater is a point of attention. The mixing of relatively oxygen-rich surface water with oxygen-depleted groundwater in the AgriMAR system can cause iron precipitation and potential clogging of filters and screens. However, during the monitoring and evaluation of the UNICEF MAR systems no significant issues with iron were encountered.

5.3 Particle size analysis

Particle size determination by sieve analysis has been performed in the soil laboratory of Dhaka University for ten samples of both the RAF 1 and RAF 2 exploration drilling. The goal of the sieve analysis was to assess the particle size distribution, which can be used to estimate the permeability of the sands (aquifer) as well as to get insight in the resistance of the clays confining the aquifer.

The soil samples that were selected for sieve analysis are presented in table 3. The depth range of the ten samples of each exploration drilling are the same to make comparison between the two sites possible. Three or four samples were selected from the shallow and deeper aquifer, while one representative sample was selected from the confining clay / silt layers in between.

The results of the sieve analysis were provided by Dhaka University simultaneously with the start of the construction works for the AgriMAR system, in December 2018. The grain size distribution of the sand layers indicate that a k-value (horizontal conductivity) of 2 – 4 m/d at the intended location and depth of the AgriMAR well screens can be expected. Additional communication with the soil laboratory took place in the following days in order to clarify some of the results. A complete overview of the particle size distribution of all 20 samples is presented in Annex 2.

Table 3. Overview of the soil samples selected for sieve analysis

Depth from (ft)	Depth to (ft)	Lithology RAF 1	RAF 2
10	15	silty clay	clayey silt
25	30	very fine sand	very fine to fine sand
45	50	very fine to fine sand	very fine to fine sand
65	70	fine sand	very fine to fine sand
85	90	very fine to fine sand	very fine to fine sand
120	125	silty clay	silty clay
145	150	very fine to fine sand	very fine to fine sand
165	170	very fine to fine sand	very fine to fine sand
185	190	very fine to fine sand	clayey silt
200	205	silty clay	very fine to fine sand
Total # samples		10	10

The results of the particle size analysis show that the aquifer at the AgriMAR site is characterized by 'fine sands' (0,124 - 0,25 mm), mixed with some 20 to 30% very fine sands (0,063 - 0,124 mm). The fraction of clay and silt (<0,063 mm) is generally 2 to 4%. Based on the relation between grain size and conductivity, as first described by Hooghoudt (1935; 1937), the *k-value* of these sands are estimated to be around 2-4 m/d, taking into account the degree of sorting and the average silt and gravel content of the sands.

At some depths 'medium sands' (0,25 mm – 0,495 mm) rather than fine sands prevail, especially in the 2nd aquifer. However, the overall increase of the transmissivity of the aquifer due to this slightly coarser sand is expected to be limited, as these medium sands are thought to be present in thin and lateral discontinuous layers (fluvial-marine deposits), therefore increasing the permeability only locally. The fraction of coarse sand (>0,495 mm) is generally very low.

Based on the overall particle size in the range of 0,124 - 0,25 mm, the optimal slot size of the filter screens should be 0,6 to 1,0 mm and the grain size of the filter pack around 1,0 to 3,0 mm.

6 Design and construction of the AgriMAR system

6.1 Location and depth of the AgriMAR well system

6.1.1 Location AgriMAR

The location of exploration drilling RAF 1, in the northern part of the plot, was selected for the construction of the AgriMAR. Some of the advantages of this site are:

- It is located further away from the river and both the AgriMAR system and the pond are therefore less sensitive for high water levels (inundations) and/or high concentrations of salt (salinization) in the river.
- The northern part of the plot is slightly more elevated than the southern part of the plot. An AgriMAR constructed in the northern part can therefore distribute the water for irrigation (more easily) under gravity-driven flow.
- The EC of the shallow groundwater (first sand layer) measured in RAF 2 is surprisingly high (around 15 mS/cm). We expect the EC of the shallow groundwater at RAF 1 to be lower.
- The EC of the deeper groundwater (second sand layer) measured in RAF 1 is slightly lower than 10 mS/cm.
- There is more elevated space available around RAF 1 for the construction of the AgriMAR system

6.1.2 Shallow or deep sand layer

Two sandy aquifers are found, both confined by clays. The first (shallow) aquifer stretches from 20-95 feet (6-31m) and the second (deep) aquifer stretches from 140-190 feet (45-57m) depth. The hydraulic conductivities are estimated to be similar, around 2 – 4 m/d based on the grain size analysis (chapter 5.3). The second (deeper) aquifer might have a higher conductivity at some depths, based on the overall coarser particle size distribution. However, the first (shallow) aquifer is preferred above the second (deep) aquifer because:

- the shallow aquifer has a significant greater thickness (25m) than the deeper aquifer (12m), so the effective transmissivity (kD) of the shallow aquifer is higher than the deeper aquifer if the total thickness of the aquifer is screened; this means more water can be infiltrated (quicker) in the shallow aquifer;
- the salinity of the shallow aquifer is expected to be lower than the salinity of the deeper aquifer, which will improve the recovery efficiency and lower the buoyancy effect
- construction and operation in the shallow aquifer is cheaper and easier.

6.2 AgriMAR design and construction

The initial question of Salt Farm Texel was to design a MAR site for an experimental site with a capacity of 1000 m^3/year. Assuming a recovery rate of 33% (the average recovery rate of the 95 UNICEF MAR systems in Bangladesh), the required infiltration capacity should be at least 3000 m^3/year. Infiltration of the MAR system can start after the first monsoon rains, when the pond starts to fill up, and can continue until the pond falls dry. Assuming a minimum of 180 infiltration days per year (June – November), the required infiltration capacity should be around 20 m^3/day. The dimensions of the AgriMAR well system (e.g. well diameter, required overhead pressure etc.) to make this infiltration rate possible are based on well capacity calculations, using Jacob Cooper equation for confined aquifers.

The AgriMAR system is aimed to be a sustainable construction, which is low-cost and low-maintenance, using local materials and labour and involving local community. In this way, the AgriMAR system is most suitable for upscaling. The scheme will function as a source of irrigation water for test plots and the water will be used either directly or after mixing water with locally available brackish water.

The initial design of the different components of the AgriMAR system was based on the evaluation of the 95 UNICEF MAR systems installed in Bangladesh. Based on the outcomes of the exploration drillings and field mission of November 2018, a final design and timeframe for the different construction activities for the AgriMAR system was made.

Under supervision of Mr. Abir Delwaruzzaman MSc., and Dr. Kazi Matin U Ahmed from Dhaka University, and Acacia Water experts Harmen van den Berg MSc. and Lukas Rolf MSc., construction works started on December 11th 2018.

6.2.1 AgriMAR site lay-out

The figure below shows the location and site layout of the AgriMAR system components.

Figure 11. Location and site layout of the AgriMAR system components

The design of the AgriMAR system is further detailed in the schematization below:

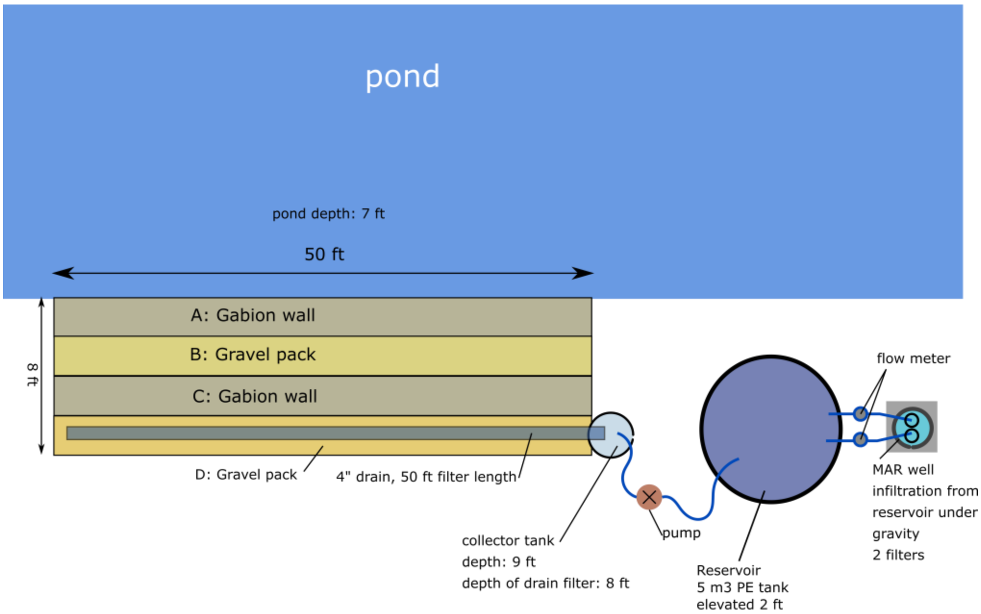


Figure 12. Schematization AgriMAR system – top view

6.2.2 Horizontal drain intake with improved filter-pack design

A horizontal drain intake for abstraction and filtration of collected rainwater from the pond was designed. The benefits of abstracting water from the pond by means of a horizontal drain intake alongside the pond, compared to the elevated sand filtration tank-construction as used in the UNICEF MAR project, is that the horizontal drain intake is easily and locally made and expected to be more low-cost and low-maintenance. Therefore, the new horizontal drain-intake is more suitable for upscaling of the AgriMAR system.

The design of the horizontal drain intake was further improved based on new insights during and after the field mission. In order to maintain the filtration capacity of the filter pack around the drain, part of the (fine) gravel/sand pack around the drain needs to be changed or cleaned. It is expected that the major part of ‘dirt’ will be collected by the jute/canvas lining of the construction, which is relatively easy to clean or replace as it is on the outside. However, part of the ‘dirt’ will manage to pass the jute/canvas lining and will slowly clog the finest gravel/sand around the drain intake.

In the improved design (see Figure 14) there are two gabion walls (cages lined with chicken wire and filled with coarse gravel; number ‘A’ and ‘C’ in the diagram above) for stability. In-between the gabion walls there is a fine-grained gravel/sand pack lined with jute canvas (‘B’ in the sketch below). Because the upper part of the drain intake / filtration pack is covered by clay, water from the pond will flow in only lateral, first through compartment B and only then through compartment D+ E (where the drain itself is located). In case of clogging of the filter pack, only the sand/gravel of compartment B needs to be cleaned/replaced, without removing the drain and surrounding sand/gravel.

A: Gabion wall; chicken wire, iron rods, coarse gravel
B: Removable filter gravel pack
C: Gabion wall; chicken wire, iron rods, coarse gravel
D: Filter gravel pack
E: 4" drain pipe, 1/24" slot size, 50 ft long
F: Jute/canvas lining (permeable)
G: Plastic tarp (impermeable)
H: Retaining wall (bamboo)

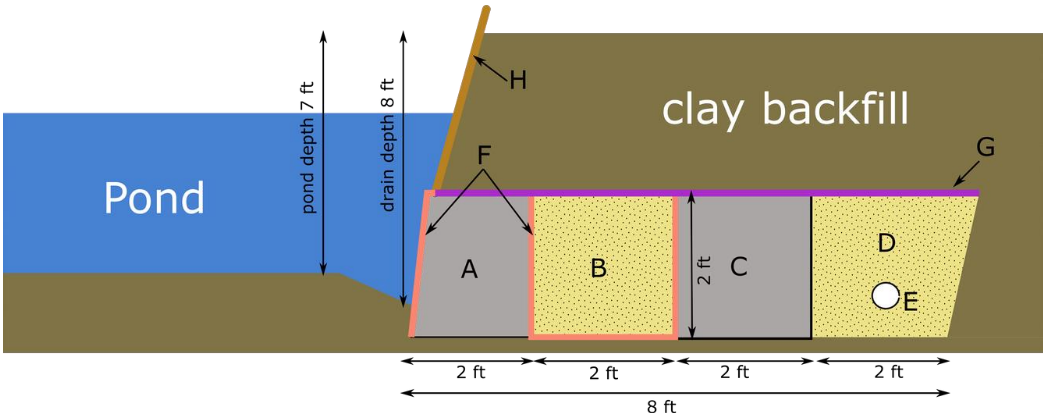


Figure 13. Schematization AgriMAR system – cross sectional view and dimensions of the drain intake

The horizontal drain was installed at a level similar to the deepest point of the adjacent pond. The drain inclines slightly towards the collector tank, located on the northern side of the drain, where the water can be pumped out of the drain. The collector tank is accessible from the surface in which the water level (head) inside the drain can be measured. By comparing the water level in the drain with the water level in the pond, clogging of the filter pack can be monitored (in that case there would be a significant difference in head).

Construction of the horizontal drain took place by first digging an excavation pit of 50 feet long and 8 feet wide (dimensions at bottom level) along the pond. In this excavation pit, the gabion walls A and C were constructed first for stability. This was followed by placing the fine gravel pack (compartment B) as well as the gravel pack + drain (compartment D and E), connected with the collector tank and all lined with jute (permeable). These compartments were covered with plastic tarp (impermeable) to avoid inflow of fine clay particles from above, after which the excavation pit was backfilled with clay. Figure 15 shows two photos taken during the construction of the horizontal drain intake.

Figure 14. Photo of the drain intake construction, showing the two gabion walls and two gravel compartments, lined with jute, being covered with plastic tarp (left) and the 4" diameter 50 ft length drain connected with the collector tank (right)

6.2.3 Elevated water reservoir

Next to the drain intake a water reservoir was placed (Figure 16) on a 2 feet elevated platform in order to increase the overhead pressure for infiltration. Initially, a concrete reservoir, being built on site, was foreseen but it turned out that, for logistically reasons, it was actually cheaper and more reliable to install a 5 m^3 PE tank reservoir instead.

The rainwater (collected in the pond, filtered through the drain intake) is pumped in the reservoir by means of a small (2-3 horsepower) diesel pump, where it infiltrates under gravity in the AgriMAR well during and after the wet months of the year (June to November). In the months that the pond water is saline or that the pond is dry (December-May) fresh water from the well will be abstracted for irrigation. The same pump can be used for both infiltration and abstraction from the well.

When the tank is empty, it needs to be refilled again which requires fuel (for the diesel pump) and manpower (to switch on/off the pump). The reservoir should be refilled continuously in order to keep the excess pressure high and thus maximize the amount of fresh water that can be stored underground. Ideally, a floating water level sensor in the reservoir could be used that automatically switches on the pump as soon as the water level in the reservoir drops below a certain level and stops as soon as it is full (same principle as in the water tank on the roof or cistern of a toilet). This requires a reliable and continuous source of electricity, but is less labour- and fuel-intensive. This can be one of the first steps to take in the near future in order to improve this system.

Figure 15. Photo of the construction of an elevated platform for the water reservoir (left) and the 5000 liter water reservoir being connected with the two filters of the AgriMAR well (right)

6.2.4 Infiltration and abstraction well

The AgriMAR well was drilled at [latitude 22.567130˚, longitude 89.730580˚], a few meters away from exploration drilling RAF1 and circa 1 foot higher. The well was drilled with a manually operated mud-rotary technique, using a 20 inch diameter drill bit and drilling mud (a mix of muddy water and some cow dung) to aid flushing the cuttings out of the borehole. At a depth of 21 feet, the interface between clay (top layer) and sand (aquifer) was encountered. The well was drilled until a depth of 97 feet; the depth at which the clay layer below the sandy aquifer was encountered. A permeable 13 inch casing made of steel rings and plastic mesh net was used for stability to keep the hole open. In the upper clay layer, a 21mm thick 16 inch diameter impervious PVC casing was installed for stability and to protect the borehole from clay entering the borehole. Inside the steel casing two 4 inch diameter PVC casings were installed, one with a screened part from 23 – 59 feet depth (shallow filter) and the other with a filter from 59 – 95 feet depth (deep filter) and a 1 feet sand trap below each filter. The protective PVC casing was sealed with a clay seal (using self-made clay-pebbles) at the 21 feet depth clay-sand interface, and the remaining open hole was filled with concrete until the surface. The schematisation of the AgriMAR well system is presented in figure 17, and some photos of the borehole drilling and well construction are included in figure 18.

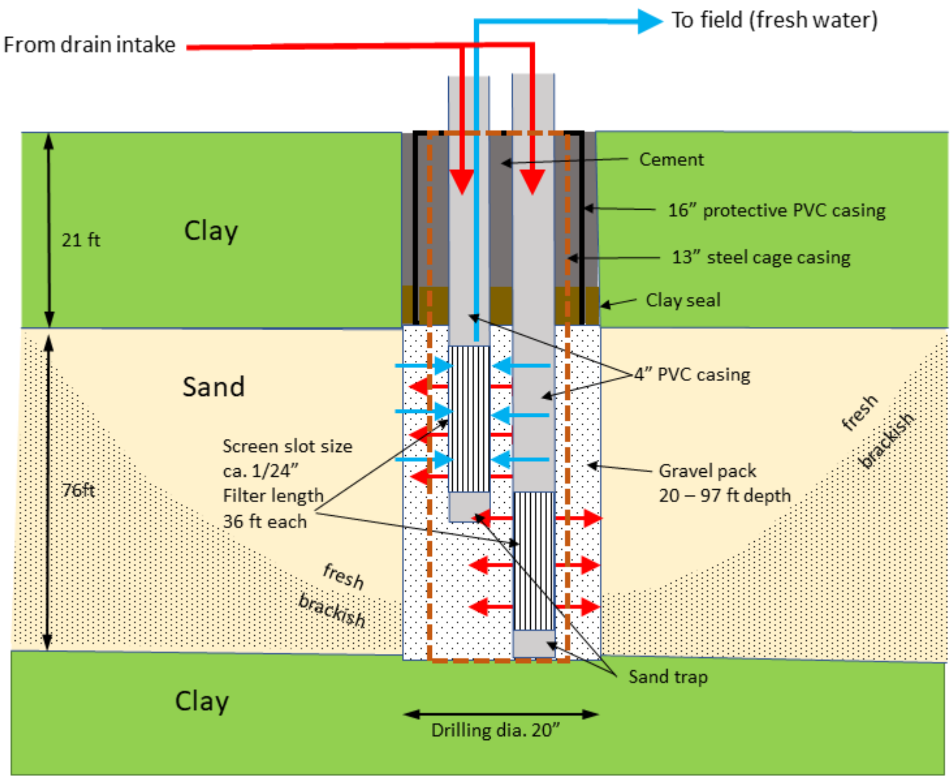


Figure 16. Schematization AgriMAR system – the infiltration and abstraction well with the shallow filter screen at 23 – 59 feet depth and the deep filter screen at 59 – 95 feet depth.

Notes on the AgriMAR infiltration and abstraction well design:

- during infiltration (gravity driven) both screens are used, during recovery (abstraction, water being pumped out) only the upper screen will be used;
- rainwater (collected in the pond; filter by the drain intake) will be pumped into a reservoir, from where this water sinks under gravity through the two infiltration filters into the aquifer;
- here the water will form a 'bubble' of fresh water, 'floating' on the brackish ambient groundwater;
- The observed infiltration capacity during the first test runs was >9 m^3/hour
- The design infiltration capacity of 20 m^3/day should be achieved easily. Assuming 180 infiltration days per year (Jun-Nov), this corresponds with a total infiltration of 3600 m3/year;
- assuming a recovery efficiency of 33%, a total of 1200 m^3/year of fresh water can be abstracted from the AgriMAR system, during a period of 6 months (Dec-May);

Figure 17. Photos of the AgriMAR well drilling and construction, showing the manual mud rotary drilling in action (upper right), the placement of the PVC protective casing (upper left) and the inner steel-ring/plastic-mesh casing (lower left), the self-made 'bentonite pebbles' or small balls of clay (lower right) and the washing and sieving of the sand that has been used for the filter pack around the filter screens as well as around the horizontal drain (middle right)

6.3 Water quality

On the 14th of December 2018, another water point inventory was performed by Acacia Water, during which Electrical Conductivity and Turbidity were measured using calibrated instruments. Where possible groundwater levels (GWS) were measured and other relevant observations done (Figure 19).

Figure 18. Photo of the EC measurement from the bridge in the middle of the river (left) and sampling of water from the exploration borehole (RAF-2) by means of an inertial pump with ball-valve

The EC measurements taken on 14-12-2018 are shown in the figure below:

Figure 19. EC measurements at and around the AgriMAR site in December 2018.

As compared to the situation in November 2018 (Figure 9), the salinity of the river water increased from 1614 µS/cm to 4650 µS/cm. This increase in salinity of surface water is also observed in other rivers in this region during the dry season (see figure 1), due to evapotranspiration and leaching of salt water from the soils and shallow groundwater combined with a lack of input of fresh (rain)water. As a result of this high EC in the river also the EC in the ponds increased, because the ponds were refilled with river water. Only the salinity of the water in the most southern pond is slightly lower than in the river, as a result of mixing with some remaining (fresh) water in this slightly deeper pond.

The salinity of the shallow groundwater did not change much and only slightly increased compared to the month before. On 20-12-2018, the EC of all the water points was measured again, but with hardly any difference from the week before (table 4).

Table 4. Water point inventory at and around the AgriMAR site, including mesaurements of Electrical Conductivity and turbidity, measured in the period November 2018 – Janaury 2019.

Water Point Inventory	Type	Coordinate latitude	Coordinate longitude	Date	Flushing before sampling (# of pumping)	EC uS/cm	Turbidity NTU	GWL m-bgl	GWL m-top tube	BH depth m-bgl	Observations
AgriMAR (shallow)	**STW**	22,56713	89,73058	22/01/2019		6740					Top piezometer x cm above groundlevel
Screen: 25-61 ft											
AgriMAR (deep)	**STW**	22,56713	89,73058	22/01/2019		12230					Top piezometer x cm above groundlevel
Screen: 61-94 ft											
RAF 2 (south)	**STW**	22,56573	89,73044	05/11/2018	100x	13860	240	0,39	0,53		Top piezometer 14 cm above groundlevel
Eploration drilling					200x	14600	200				
Screen: 90-100 ft					300x	15200	220				
					400x	15500	190	0,43			After removing the pump
				14/12/2018	10x	14800		0,65	0,79		sampling with ball-valve tube
				20/12/2018	0x & 100x	15300	32	0,68	0,82		sampling with ball-valve tube
RAF 1 (north)	**STW**	22,56713	89,73059	05/11/2018	1x	9940	30	0,60	0,67		Top piezometer 7 cm above groundlevel
Exploration drilling					100x	9880	5				
Screen: 170-180 ft					200x	9800	50				
					300x	9740	48				
					400x	9740	82				
				14/12/2018	10x	10100		0,8	0,87		sampling with ball-valve tube T in piezometer is much warmer (28 deg C) than water in pond (23 deg C) --> gw sample is coming from (warm) tube?
				20/12/2018	0x & 100x	10100	<5.0	0,86	0,93		sampling with ball-valve tube
Pond 1 (north)	**SW**	22,56715	89,73052	05/11/2018		3380	100				Pond far away from river (north)
				14/12/2018		5200					EC of pond measured on both west- and eastside Pond is around 2 feet deep (below current water level), but a deeper part is along the drain intake side. Pond is connected (removable dam) with the canal in the north and Pond 2 in the south
				20/12/2018		5140					5150 uS/cm on other side of pond
				22/01/2019		5180					
Pond 2	**SW**	22,56618	89,73008	05/11/2018		2710	93				Central pond
				14/12/2018		4500					EC of pond measured on both west- and eastside Pond is around 2 feet deep (below current water level). Pond is connected (removable dam) with Pond 1 in the north and Pond 3 in the south
				20/12/2018		4360	90				4400 uS/cm on other side of pond
Pond 3 (south)	**SW**	22,56571	89,73041	05/11/2018		2330	40				Pond close to river (south)
				14/12/2018		3850					EC of pond measured on both west- and eastside Pond is around 4 feet deep (below current water level). Pond is connected (removable dam) with Pond 2 in the north and the River in the south
				20/12/2018		4050					
Canal north of rice field	**SW**	22,56721	89,73054	05/11/2018		4690	23				
				14/12/2018		5300					5400 measured on the east side of the canal
				20/12/2018		5500					
Canal east of rice field	**SW**	xxx	xxx	05/11/2018							
				14/12/2018		3600					3400 measured on the north side (start) of the canal
				20/12/2018		3500					
River	**SW**	22,56615	89,73118	05/11/2018		1614	70				Dam is closed
				14/12/2018		4650					EC measured on the side (4650) as well as in the middle of the river (from a bridge), shallow (4650) and deep (4720). Water is rather stagnant, dam is closed, river is 3-4m deep
				20/12/2018		4650	70				
				22/01/2019		5160					
Shallow well 1	**STW**	22,56698	89,73135	05/11/2018		6870	<5			12,2	Not used for drinking; iron precipitation on the BH slab and handpump (high iron content) - brownish/reddish colour of the water; but clear
				14/12/2018		6950				11,6	Borehole depth is 38 feet
Pond next to STW1	**SW**	22,56697	89,73131	05/11/2018		2210	70				Mixed rainwater and canal water (connected with river through duiker under the road)
				14/12/2018		2800					2950 measured on the north side of the pond
				20/12/2018		2950					
Shallow well 2	**STW**	22,56625	89,73191	05/11/2018		4570	40			50,3	
Shallow well 3	**STW**	22,56561	89,72891	05/11/2018		7280	9			9,1	Brownish
Shallow well 4	**STW**	22,56560	89,72873	05/11/2018		8400	<5			15,2	
Deep well 1	**DTW**	22,56914	89,72504	05/11/2018		3790	<5			240,0	
				14/12/2018		3800					Water is very clear, T = 27.1 degrees C

7 Testing and monitoring AgriMAR system

First test of system on 24/01/2019

Ambient groundwater before start infiltration
EC at shallow filter: 6.74 mS/cm
EC at deep filter: 12.23 mS/cm

Water in pond at start infiltration
EC in pond: 5.18 mS/cm

Time needed to fill the tank (5000 liter)
20 minutes → capacity pump/drain is 15.0 m^3/hr

Time needed to infiltrate 5000 liter in the AgriMAR wells
32 minutes when both wells are open → infiltration capacity well is 9.4 m^3/hr
49 minutes to fill the well with only the upper screen → infiltration capacity upper screen is 9.4 m^3/hr
49 minutes to fill the well with only the lower screen → infiltration capacity lower screen is 9.4 m^3/hr

Water flow meter readings
In the period between the 24th and 28th of January 2019 various tests were performed in which a total of 45 m^3 of water was infiltrated (table 5). The first measurements suggest that the infiltration capacity of the shallow filter and deep filter screen are nearly the same. The second reading, taken a week later, suggests that there is a difference in infiltration rates between the shallow filter and deep filter. The shallow filter has a higher infiltration capacity, which is likely due to the less saline ambient groundwater at the top of the aquifer. There might also be difference in the hydraulic conductivity of the shallow and deep aquifer layers.

Table 5: Flow meter readings (in m^3) of the total amount of water infiltrated in the shallow screen and the deep screen of the AgriMAR well.

	SHALLOW SCREEN	DEEP SCREEN
24/01/2019	Flow meter installed	Flow meter installed
28/01/2019	22.15 m3	22.95 m3
03/02/2019	109.35 m3	59.49 m3

Observations drain intake

- When start pumping the head in the drain (observed as water level in the barrel) goes down a few inches but then stabilizes quickly and remains stable → stable and high flow towards the drain
- The turbidity of water pumped from drain intake is visibly lower than water in pond (pond water turbidity: 85 NTU; filter water: 50 NTU) → sand & jute filter works!

Current situation (as per 22/01/2019, at the start of infiltration):

Figure 20. EC measurements at and around the AgriMAR site at the start of the infiltration, on 22 January 2019

Figure 21. Photos of the testing of the AgriMAR system, showing the flow meters of the infiltration of the shallow and deep filter screen (right), the water being pumped from the drain via the collector tank (upper left), filling of the 5000 liter PE reservoir (middle left), and comparing the higher turbidity of the pond water with the filtered water (lower left)

8 Upscaling the AgriMAR system

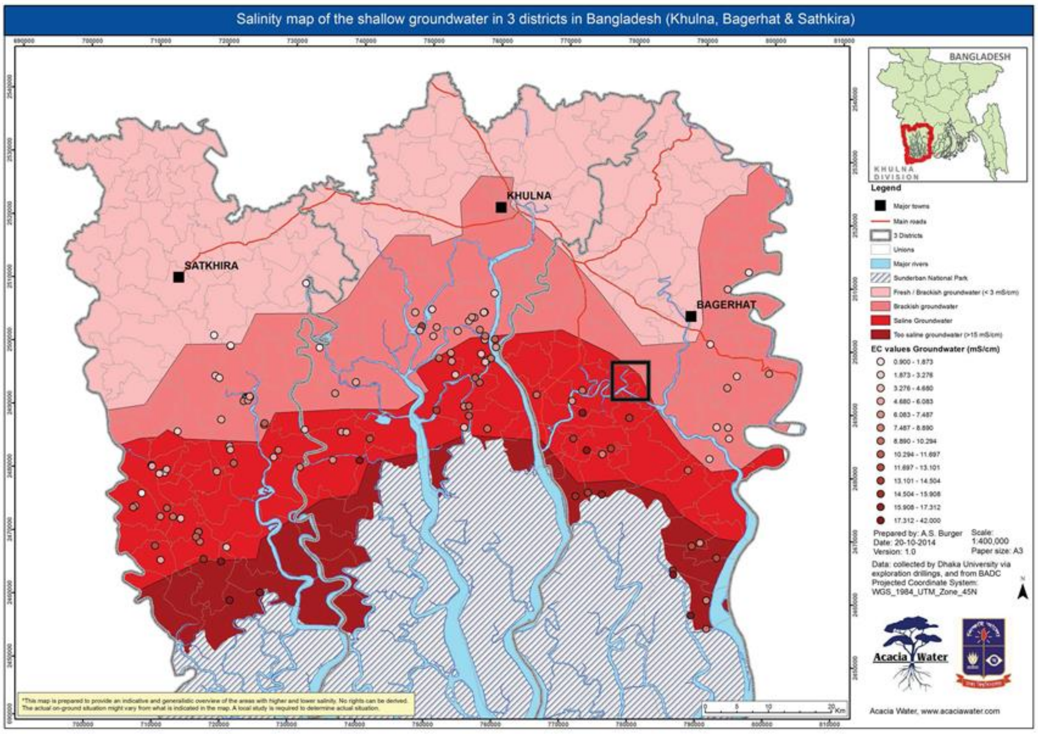
The feasibility of Managed Aquifer Recharge in combination with irrigated agriculture (AgriMAR) depends on geohydrological and socio-economic factors. Directly combining these two factors is the best approach to define where and for which crops this combination would be feasible and what the optimal design of these AgriMAR systems would be.

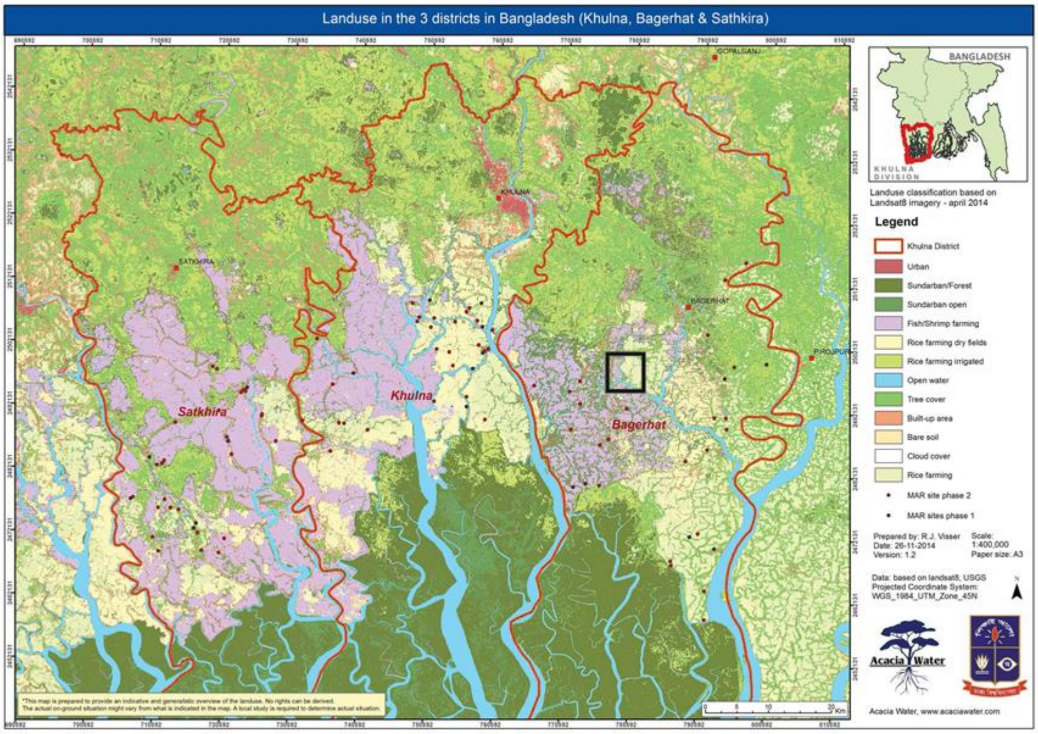
The feasibility assessment forms a strong basis for upscaling and dissemination. The assessment will combine economic, agronomic and hydrological information to form a net-benefit-cost-ratio of MAR within all circumstances. The combined approach is important as the hydrogeology and economy of MAR is very much linked in terms of costs, design and irrigation practices. Costs which need to be earned back by the farmer in the form of higher yields after irrigation. The assessment takes in to account:

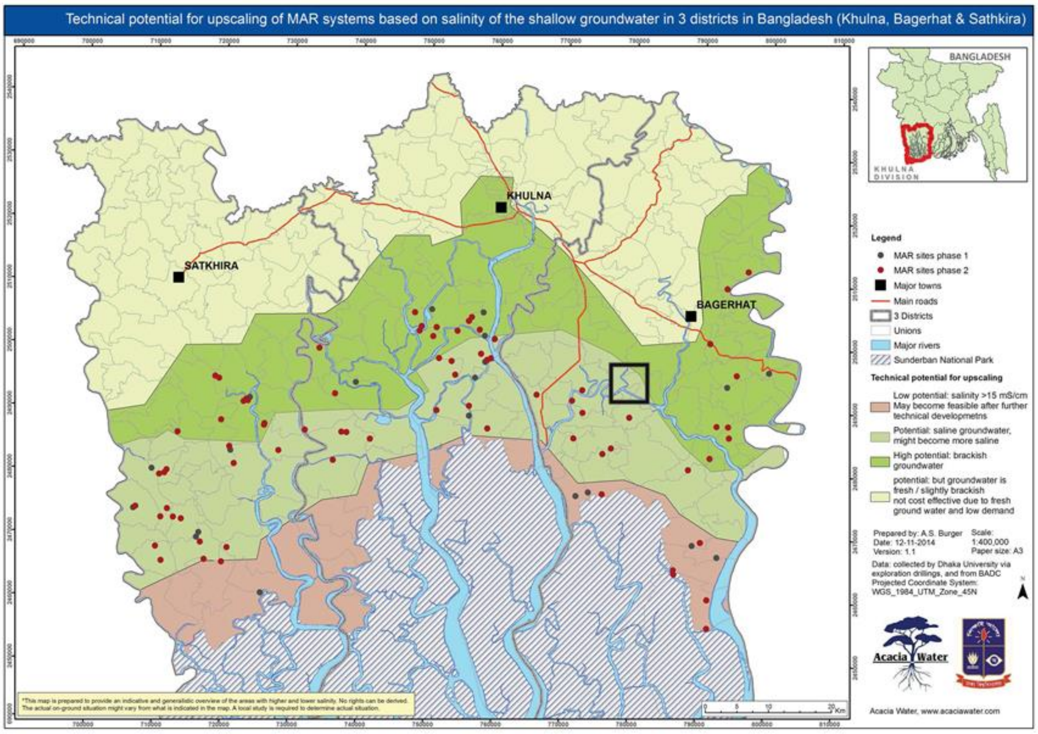
- Problem description;
- AgriMAR costs;
- AgriMAR benefits;
- Quantifying the effects if data available, including;
    - Crop price;
    - Crop yield;
    - Growing period;
    - Crop water requirements;
    - Irrigation efficiency;
- Most feasible and promising areas for implementation.
-

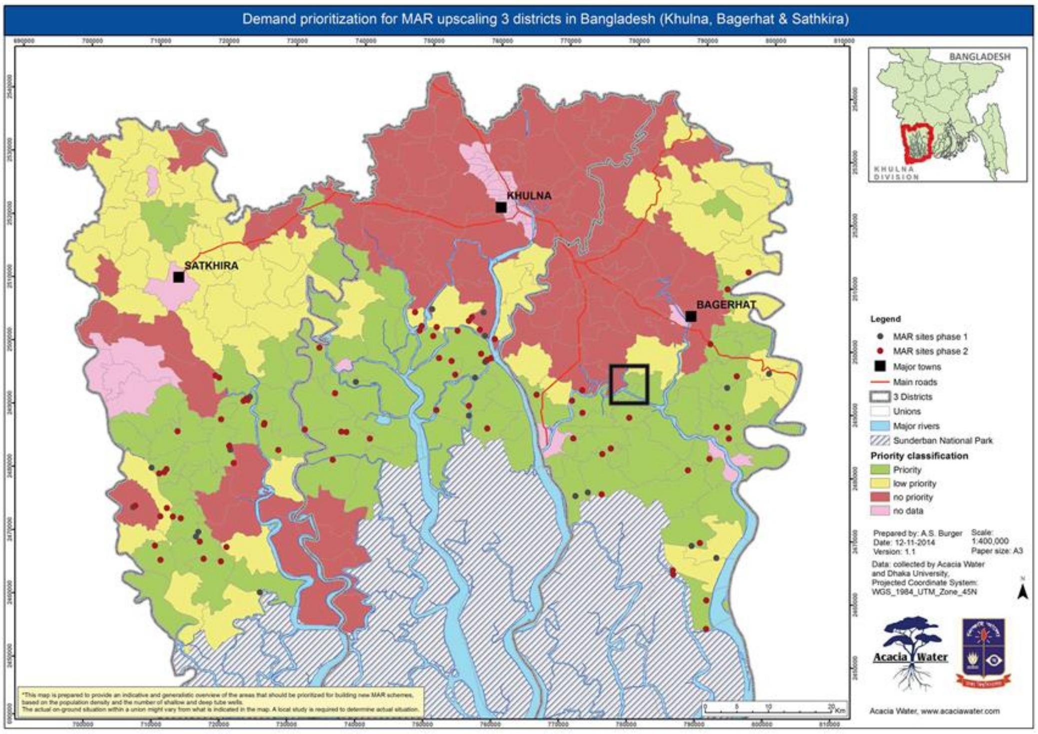
An integrated **socio-agro-economic and hydrogeological feasibility assessment** will be presented in March. In this assessment, the first monitoring results of the AgriMAR system in Bagerhat will be included, together with a step for step approach for replication and upscaling of the AgriMAR system in Bangladesh. This assessment will also include a monitoring plan for the existing AgriMAR system, and an agribusiness implementation plan for introduction of salt tolerant crops combined with MAR for irrigation.

Annex 1 –
Thematic maps AgriMAR site


Salinity map of the shallow groundwater in 3 districts in Bangladesh (Khulna, Bagerhat & Sathkira)
BANGLADESH
KHULNA DIVISION
KHULNA
SATKHIRA
BAGERHAT
Legend
Major towns
Main roads
3 Districts
Unions
Major rivers
Sunderban National Park
Fresh / Brackish groundwater (< 3 mS/cm)
Brackish groundwater
Saline Groundwater
Too saline groundwater (>15 mS/cm)
EC values Groundwater (mS/cm)
0.900 - 1.873
1.873 - 3.276
3.276 - 4.680
4.680 - 6.083
6.083 - 7.487
7.487 - 8.890
8.890 - 10.294
10.294 - 11.697
11.697 - 13.101
13.101 - 14.504
14.504 - 15.908
15.908 - 17.312
17.312 - 42.000
Prepared by: A.S. Burger
Date: 20-10-2014
Version: 1.0
Scale: 1:400,000
Paper size: A3
Data: collected by Dhaka University via exploration drillings, and from BADC
Projected Coordinate System: WGS_1984_UTM_Zone_45N
Acacia Water
Acacia Water, www.acaciawater.com

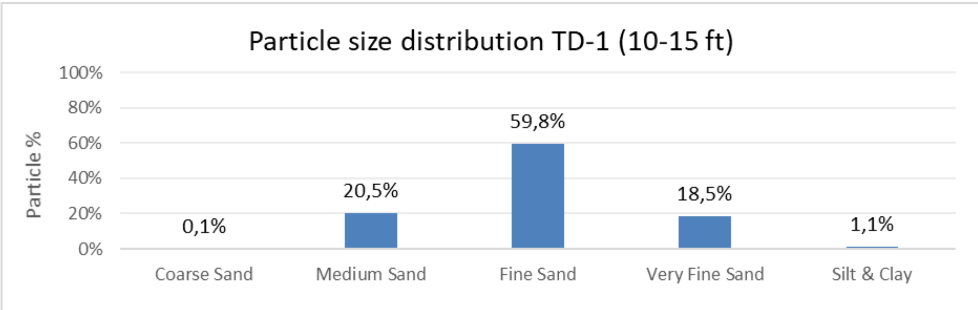

Landuse in the 3 districts in Bangladesh (Khulna, Bagerhat & Sathkira)
BANGLADESH
KHULNA DIVISION
Satkhira
Khulna
Bagerhat
Landuse classification based on Landsat8 imagery - april 2014
Legend
Khulna District
Urban
Sundarban/Forest
Sundarban open
Fish/Shrimp farming
Rice farming dry fields
Rice farming irrigated
Open water
Tree cover
Built-up area
Bare soil
Cloud cover
Rice farming
MAR site phase 2
MAR sites phase 1
Prepared by: R.J. Visser
Date: 26-11-2014
Version: 1.2
Scale: 1:400,000
Paper size: A3
Data: based on landsat8, USGS
Projected Coordinate System: WGS_1984_UTM_Zone_45N
Acacia Water
Acacia Water, www.acaciawater.com


Technical potential for upscaling of MAR systems based on salinity of the shallow groundwater in 3 districts in Bangladesh (Khulna, Bagerhat & Sathkira)
KHULNA
SATKHIRA
BAGERHAT
BANGLADESH
KHULNA DIVISION
Legend
MAR sites phase 1
MAR sites phase 2
Major towns
Main roads
3 Districts
Unions
Major rivers
Sunderban National Park
Technical potential for upscaling
Low potential: salinity >15 mS/cm May become feasible after further technical developmetns
Potential: saline groundwater, might become more saline
High potential: brackish groundwater
potential: but groundwater is fresh / slightly brackish not cost effective due to fresh ground water and low demand
Prepared by: A.S. Burger
Date: 12-11-2014
Version: 1.1
Scale: 1:400,000
Paper size: A3
Data: collected by Dhaka University via exploration drillings, and from BADC
Projected Coordinate System: WGS_1984_UTM_Zone_45N
Acacia Water, www.acaciawater.com


Demand prioritization for MAR upscaling 3 districts in Bangladesh (Khulna, Bagerhat & Sathkira)
KHULNA
SATKHIRA
BAGERHAT
BANGLADESH
KHULNA DIVISION
Legend
MAR sites phase 1
MAR sites phase 2
Major towns
Main roads
3 Districts
Unions
Major rivers
Sunderban National Park
Priority classification
Priority
low priority
no priority
no data
Prepared by: A.S. Burger
Date: 12-11-2014
Version: 1.1
Scale: 1:400,000
Paper size: A3
Data: collected by Acacia Water and Dhaka University,
Projected Coordinate System: WGS_1984_UTM_Zone_45N
Acacia Water, www.acaciawater.com

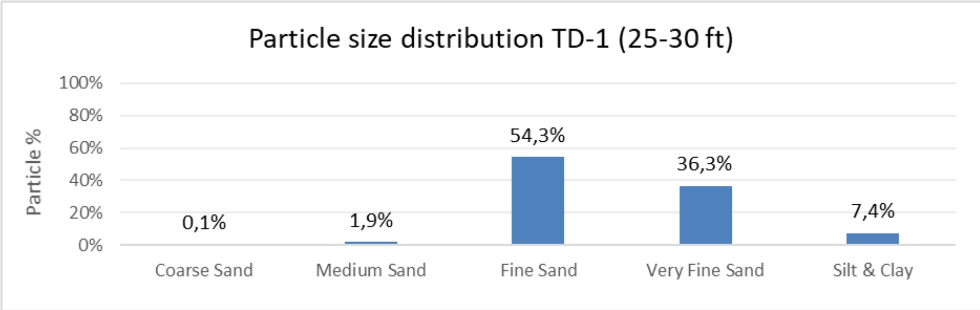
Annex 2
Particle size analysis

Test Drilling 1

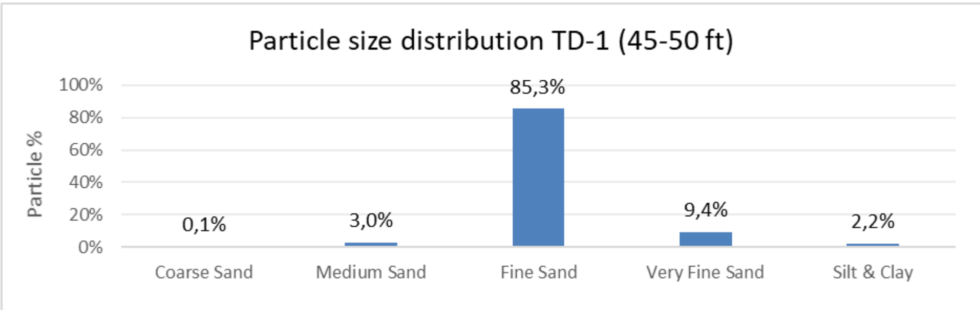


Sample No: TD-1 (10-15 ft) Soil description: "Bluish gray silty clay" [1st aquitard]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0,05	0,05	0,1%	Coarse Sand
60	2	0,25	10,28	10,33	20,5%	Medium Sand
120	3	0,124	29,92	40,25	59,8%	Fine Sand
230	4	0,063	9,24	49,49	18,5%	Very Fine Sand
Pan	>4	<0.063	0,57	50,06	1,1%	Silt & Clay
					100,0%	

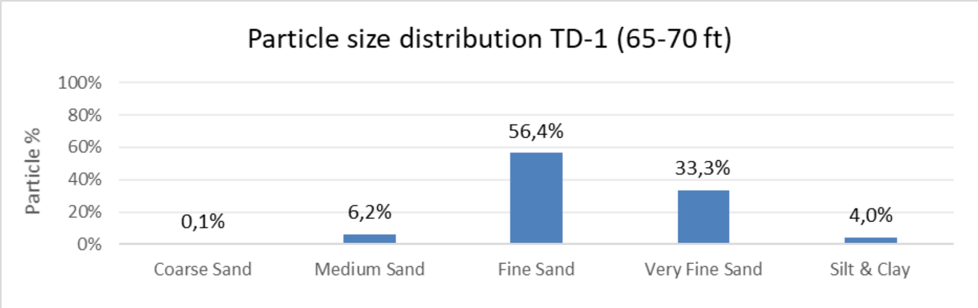
Note: The soil description in the field gives 'silty clay', while according to the sieve analysis the samples contains mainly fine sand (60%) and almost no silt & clay (1%). Likely a mistake was made with the labelling of the soil sample bags or a not representative sample was analysed. During the field visit in December 2018, it has been confirmed that the upper ~20 feet consists of clay with hardly any sand.



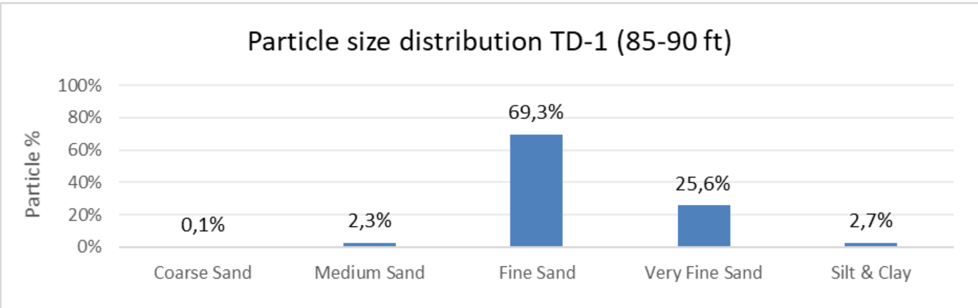
Sample No: TD-1 (25-30 ft) Soil description: "Bluish gray very fine sand" [1st aquifer]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0,09	0,09	0,1%	Coarse Sand
60	2	0,25	1,85	1,94	1,9%	Medium Sand
120	3	0,124	54,23	56,17	54,3%	Fine Sand
230	4	0,063	36,32	92,49	36,3%	Very Fine Sand
Pan	>4	<0.063	7,43	99,92	7,4%	Silt & Clay
					100,0%	



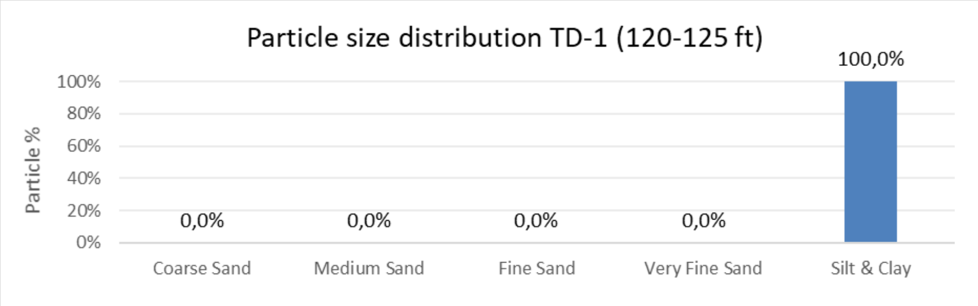
Sample No: TD-1 (45-50 ft) Soil description: "Bluish gray very fine to fine sand" [1st aquifer]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0,14	0,14	0,1%	Coarse Sand
60	2	0,25	3,02	3,16	3,0%	Medium Sand
120	3	0,124	85,25	88,41	85,3%	Fine Sand
230	4	0,063	9,38	97,79	9,4%	Very Fine Sand
Pan	>4	<0.063	2,17	99,98	2,2%	Silt & Clay
					100,0%	



Sample No: TD-1 (65-70 ft) Soil description: "Bluish gray fine sand" [1st aquifer]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0,12	0,12	0,1%	Coarse Sand
60	2	0,25	6,15	6,27	6,2%	Medium Sand
120	3	0,124	56,34	62,61	56,4%	Fine Sand
230	4	0,063	33,23	95,84	33,3%	Very Fine Sand
Pan	>4	<0.063	4,02	99,86	4,0%	Silt & Clay
					100,0%	

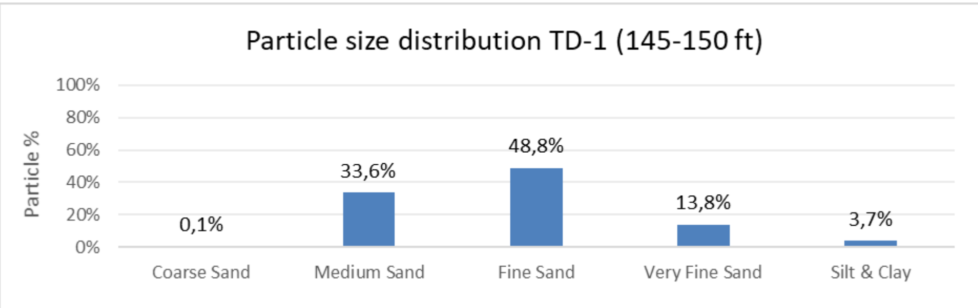


Sample No: TD-1 (85-90 ft) Soil description: "Bluish gray very fine to fine sand" [1st aquifer]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0,09	0,09	0,1%	Coarse Sand
60	2	0,25	2,3	2,39	2,3%	Medium Sand
120	3	0,124	69,25	71,64	69,3%	Fine Sand
230	4	0,063	25,56	97,2	25,6%	Very Fine Sand
Pan	>4	<0.063	2,67	99,87	2,7%	Silt & Clay
					100,0%	

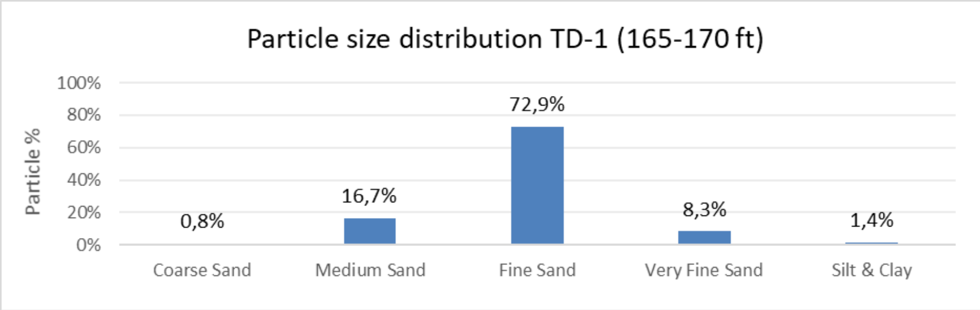


Sample No: TD-1 (120-125 ft) Soil description: "Bluish gray silty clay" [2nd aquitard]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0	0	0,0%	Coarse Sand
60	2	0,25	0	0	0,0%	Medium Sand
120	3	0,124	0	0	0,0%	Fine Sand
230	4	0,063	0	0	0,0%	Very Fine Sand
Pan	>4	<0.063	100	100	100,0%	Silt & Clay
					100,0%	

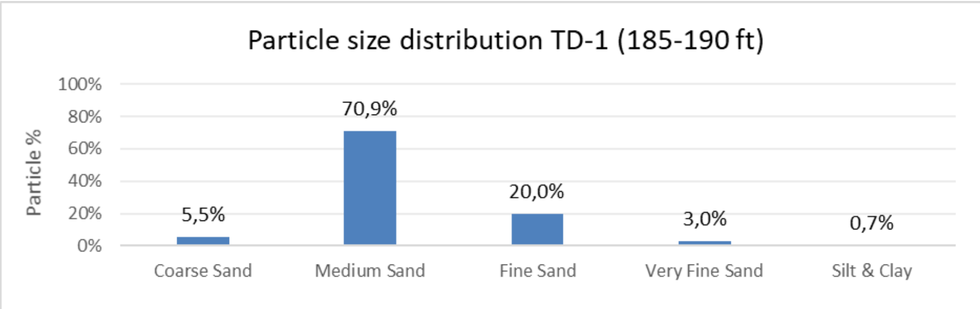
Note from the soil lab of Dhaka University: For this sample, particle size analysis was not possible using sieve method. The technician took wait of lumpy fragments retained in coarser sieves; all should be assumed as silt and clay; may be some sand is present but it was not possible to differentiate.



Sample No: TD-1 (145-150 ft) Soil description: "Gray very fine to fine sand" [2nd aquifer]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0,12	0,12	0,1%	Coarse Sand
60	2	0,25	33,51	33,63	33,6%	Medium Sand
120	3	0,124	48,67	82,3	48,8%	Fine Sand
230	4	0,063	13,8	96,1	13,8%	Very Fine Sand
Pan	>4	<0.063	3,71	99,81	3,7%	Silt & Clay
					100,0%	

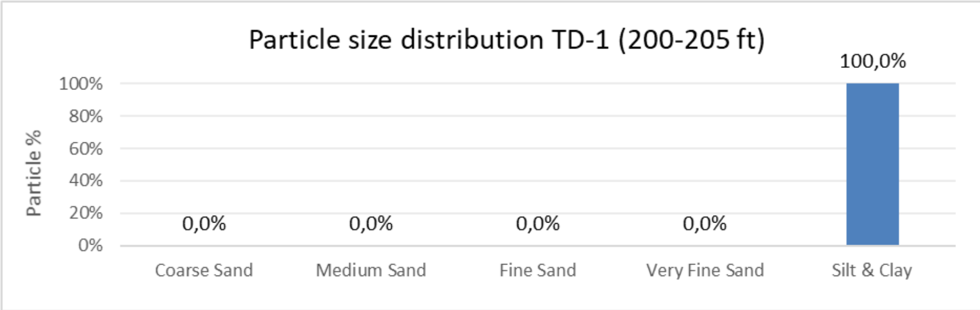


Sample No: TD-1 (165-170 ft) Soil description: "Gray very fine to fine sand" [2nd aquifer]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0,77	0,77	0,8%	Coarse Sand
60	2	0,25	16,65	17,42	16,7%	Medium Sand
120	3	0,124	72,75	90,17	72,9%	Fine Sand
230	4	0,063	8,33	98,5	8,3%	Very Fine Sand
Pan	>4	<0.063	1,36	99,86	1,4%	Silt & Clay
					100,0%	



Sample No: TD-1 (185-190 ft) Soil description: "Gray very fine to fine sand" [2nd aquifer]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	5,51	5,51	5,5%	Coarse Sand
60	2	0,25	70,77	76,28	70,9%	Medium Sand
120	3	0,124	19,95	96,23	20,0%	Fine Sand
230	4	0,063	2,96	99,19	3,0%	Very Fine Sand
Pan	>4	<0.063	0,69	99,88	0,7%	Silt & Clay
					100,0%	

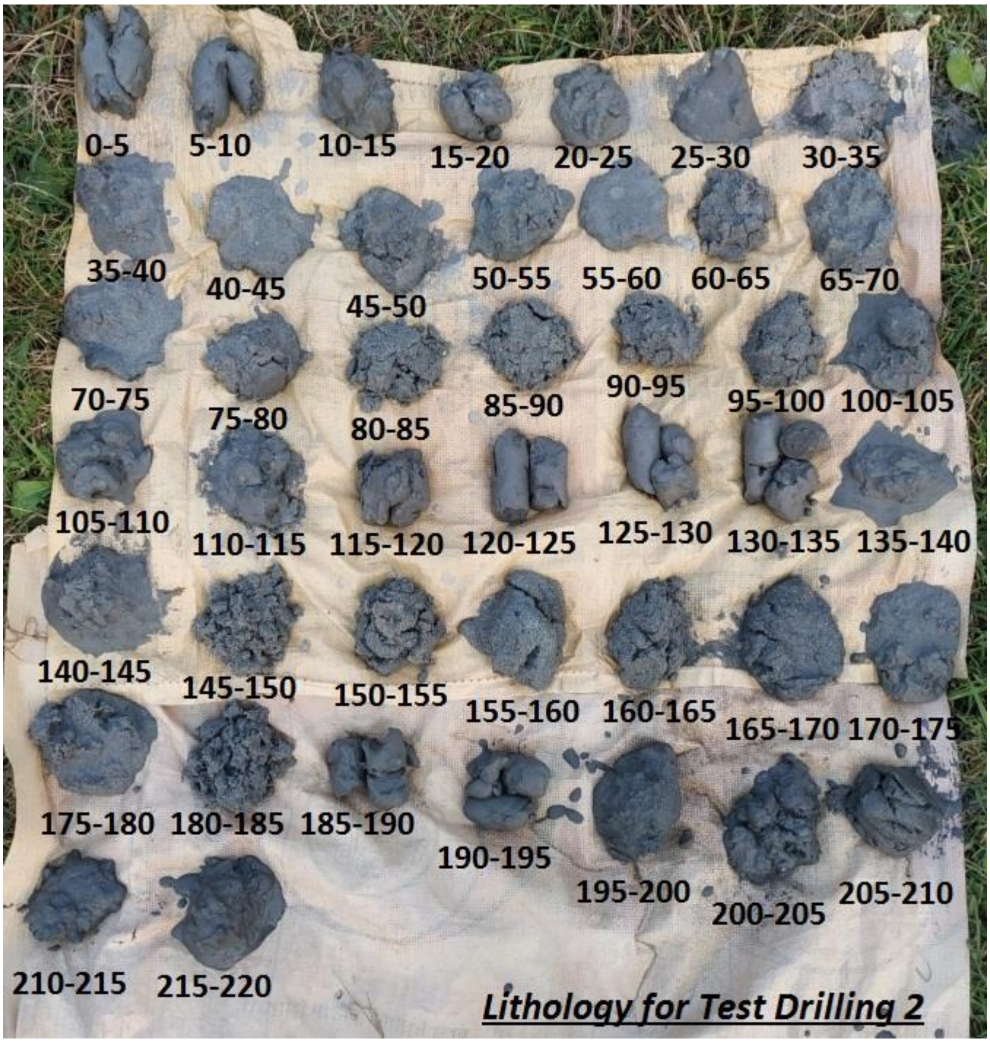
Note: the sieve analysis shows 71% is medium sand. This is different from the soil description given in the field ("very fine to fine sand").

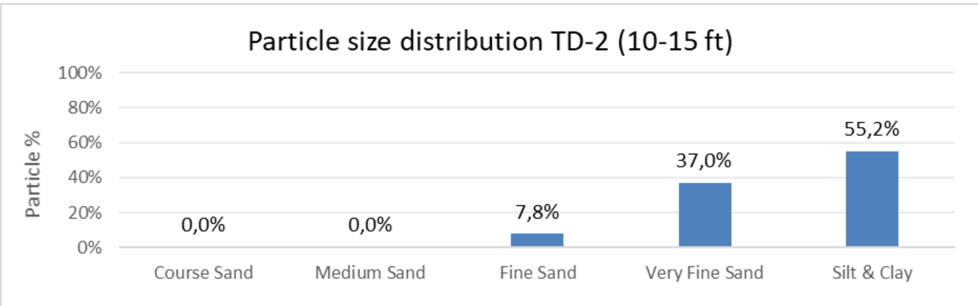


Sample No: TD-1 (200-205 ft) Soil description: "Bluish gray silty clay organic material" [3rd aquitard]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0	0	0,0%	Coarse Sand
60	2	0,25	0	0	0,0%	Medium Sand
120	3	0,124	0	0	0,0%	Fine Sand
230	4	0,063	0	0	0,0%	Very Fine Sand
Pan	>4	<0.063	100	100	100,0%	Silt & Clay
					100,0%	

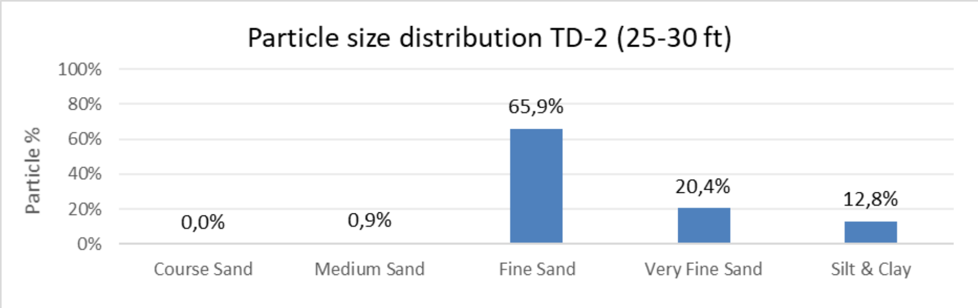
Note from the soil lab of Dhaka University: For this sample, particle size analysis was not possible using sieve method. The technician took wait of lumpy fragments retained in coarser sieves; all should be assumed as silt and clay; may be some sand is present but it was not possible to differentiate.

Test Drilling 2

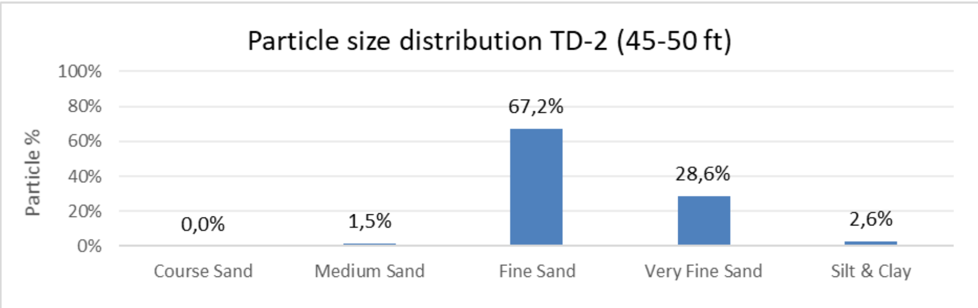




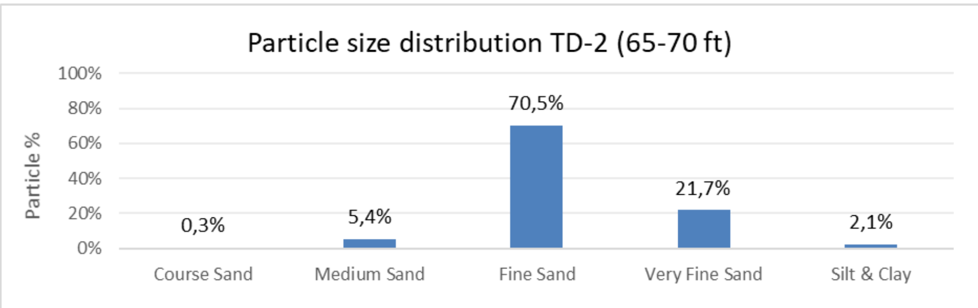
Sample No: TD-2 (10-15 ft) Soil description: "Bluish gray clayey silt" [1st aquitard]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0	0	0,0%	Course Sand
60	2	0,25	0	0	0,0%	Medium Sand
120	3	0,124	3,87	3,87	7,8%	Fine Sand
230	4	0,063	18,48	22,35	37,0%	Very Fine Sand
Pan	>4	<0.063	27,54	49,89	55,2%	Silt & Clay
					100,0%	



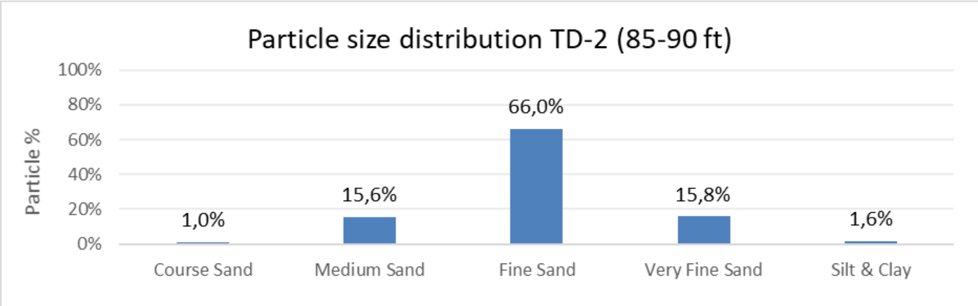
Sample No: TD-2 (25-30 ft) Soil description: "Gray very fine to fine sand" [1st aquifer]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0	0	0,0%	Course Sand
60	2	0,25	0,47	0,47	0,9%	Medium Sand
120	3	0,124	32,89	33,36	65,9%	Fine Sand
230	4	0,063	10,17	43,58	20,4%	Very Fine Sand
Pan	>4	<0.063	6,37	49,9	12,8%	Silt & Clay
					100,0%	



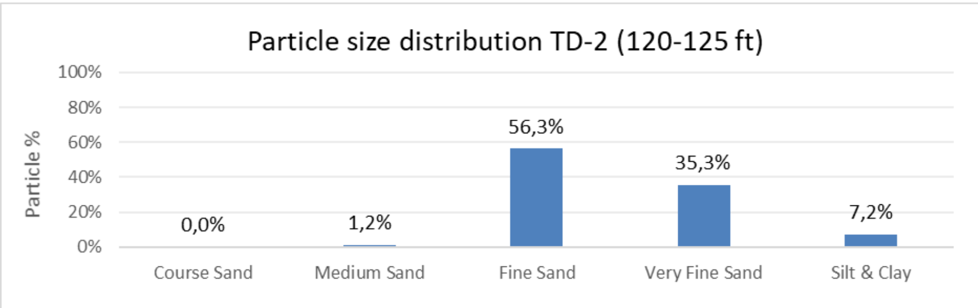
Sample No: TD-2 (45-50 ft) Soil description: "Gray very fine to fine sand" [1st aquifer]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0,04	0,04	0,0%	Course Sand
60	2	0,25	1,52	1,56	1,5%	Medium Sand
120	3	0,124	67,17	68,73	67,2%	Fine Sand
230	4	0,063	28,61	97,34	28,6%	Very Fine Sand
Pan	>4	<0.063	2,6	99,94	2,6%	Silt & Clay
					100,0%	



Sample No: TD-2 (65-70 ft) Soil description: "Gray very fine to fine sand" [1st aquifer]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0,3	0,3	0,3%	Course Sand
60	2	0,25	5,38	5,68	5,4%	Medium Sand
120	3	0,124	70,39	76,07	70,5%	Fine Sand
230	4	0,063	21,72	97,79	21,7%	Very Fine Sand
Pan	>4	<0.063	2,1	99,89	2,1%	Silt & Clay
					100,0%	

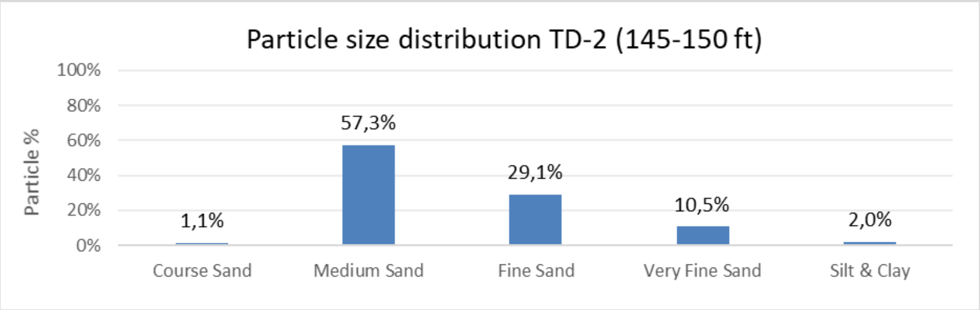


Sample No: TD-2 (85-90 ft) Soil description: "Gray very fine to fine sand" [1st aquifer]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0,97	0,97	1,0%	Course Sand
60	2	0,25	15,56	16,53	15,6%	Medium Sand
120	3	0,124	65,9	82,43	66,0%	Fine Sand
230	4	0,063	15,83	98,26	15,8%	Very Fine Sand
Pan	>4	<0.063	1,63	99,89	1,6%	Silt & Clay
					100,0%	



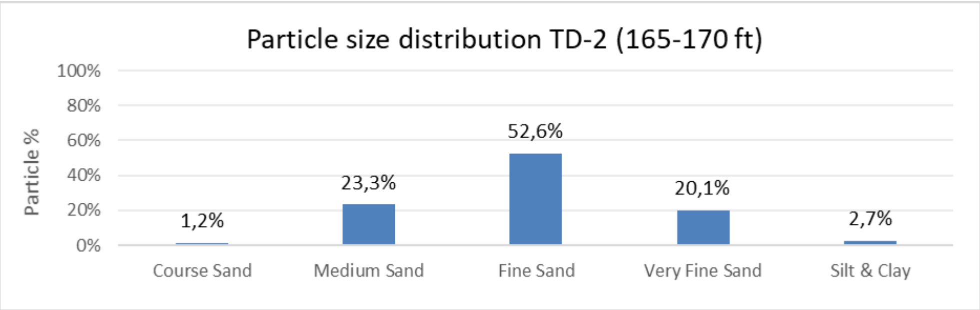
Sample No: TD-2 (120-125 ft) Soil description: "Bluish gray silty clay with wood fragment" [2nd aquitard]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0	0	0,0%	Course Sand
60	2	0,25	0,59	0,59	1,2%	Medium Sand
120	3	0,124	28,08	28,67	56,3%	Fine Sand
230	4	0,063	17,6	46,27	35,3%	Very Fine Sand
Pan	>4	<0.063	3,6	49,87	7,2%	Silt & Clay
					100,0%	

Note: The soil description in the field gives 'silty clay', while according to the sieve analysis the samples contains mainly fine sand (56%) and very fine sand (35%) and only 7% silt & clay. Possibly, a mistake was made with the labelling of the soil sample bags or a not representative sample was analysed.

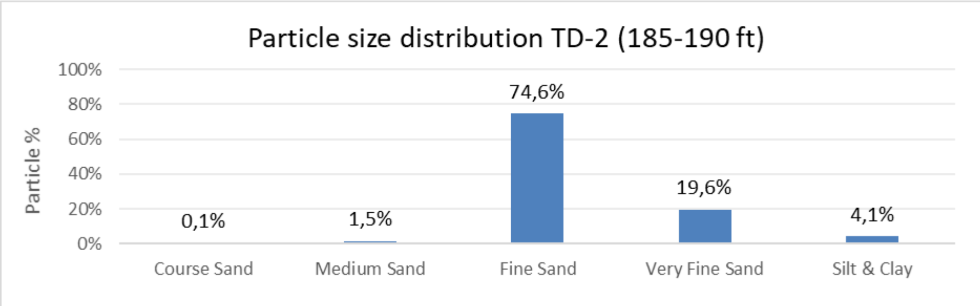


Sample No: TD-2 (145-150 ft) Soil description: "Gray very fine to fine sand" [2nd aquifer]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	1,08	1,08	1,1%	Course Sand
60	2	0,25	57,26	58,34	57,3%	Medium Sand
120	3	0,124	29,06	87,4	29,1%	Fine Sand
230	4	0,063	10,5	97,9	10,5%	Very Fine Sand
Pan	>4	<0.063	1,96	99,86	2,0%	Silt & Clay
					100,0%	

Note: the sieve analysis shows 57% is medium sand. This is different from the soil description given in the field ("very fine to fine sand").

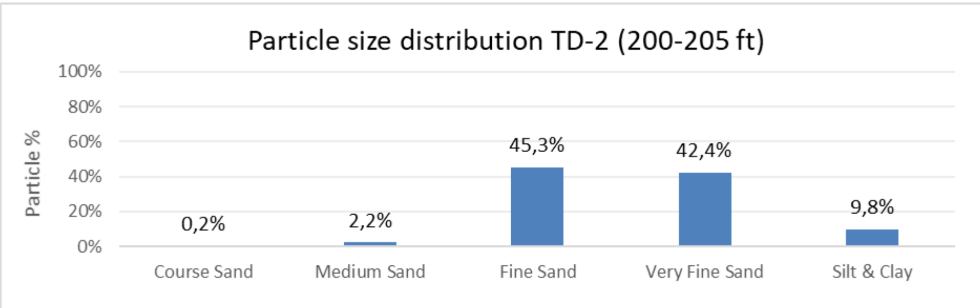


Sample No: TD-2 (165-170 ft) Soil description: "Gray very fine to fine sand" [2nd aquifer]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	1,19	1,19	1,2%	Course Sand
60	2	0,25	23,31	24,5	23,3%	Medium Sand
120	3	0,124	52,59	77,09	52,6%	Fine Sand
230	4	0,063	20,1	97,19	20,1%	Very Fine Sand
Pan	>4	<0.063	2,72	99,91	2,7%	Silt & Clay
					100,0%	



Sample No: TD-2 (185-190 ft) Soil description: "Bluish gray clayey silt with organic material" [3rd aquitard]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0,06	0,06	0,1%	Course Sand
60	2	0,25	0,75	0,81	1,5%	Medium Sand
120	3	0,124	37,24	38,05	74,6%	Fine Sand
230	4	0,063	9,8	47,85	19,6%	Very Fine Sand
Pan	>4	<0.063	2,07	49,92	4,1%	Silt & Clay
					100,0%	

Note: The soil description in the field gives 'clayey silt', while according to the sieve analysis the samples contains mainly fine sand (75%) and very fine sand (20%) and only 4% silt & clay. Possibly, a mistake was made with the labelling of the soil sample bags or a not representative sample was analysed.



Sample No: TD-2 (200-205 ft) Soil description: "Bluish gray very fine to fine sand" [3rd aquifer]						
Mesh No	Aperture Phi	Aperture mm	Weight Retained gm	Cumulative weight gm	Particle %	Wentworth Size Class
35	1	0,495	0,15	0,15	0,2%	Course Sand
60	2	0,25	2,23	2,38	2,2%	Medium Sand
120	3	0,124	45,3	47,68	45,3%	Fine Sand
230	4	0,063	42,4	90,08	42,4%	Very Fine Sand
Pan	>4	<0.063	9,82	99,9	9,8%	Silt & Clay
					100,0%	

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