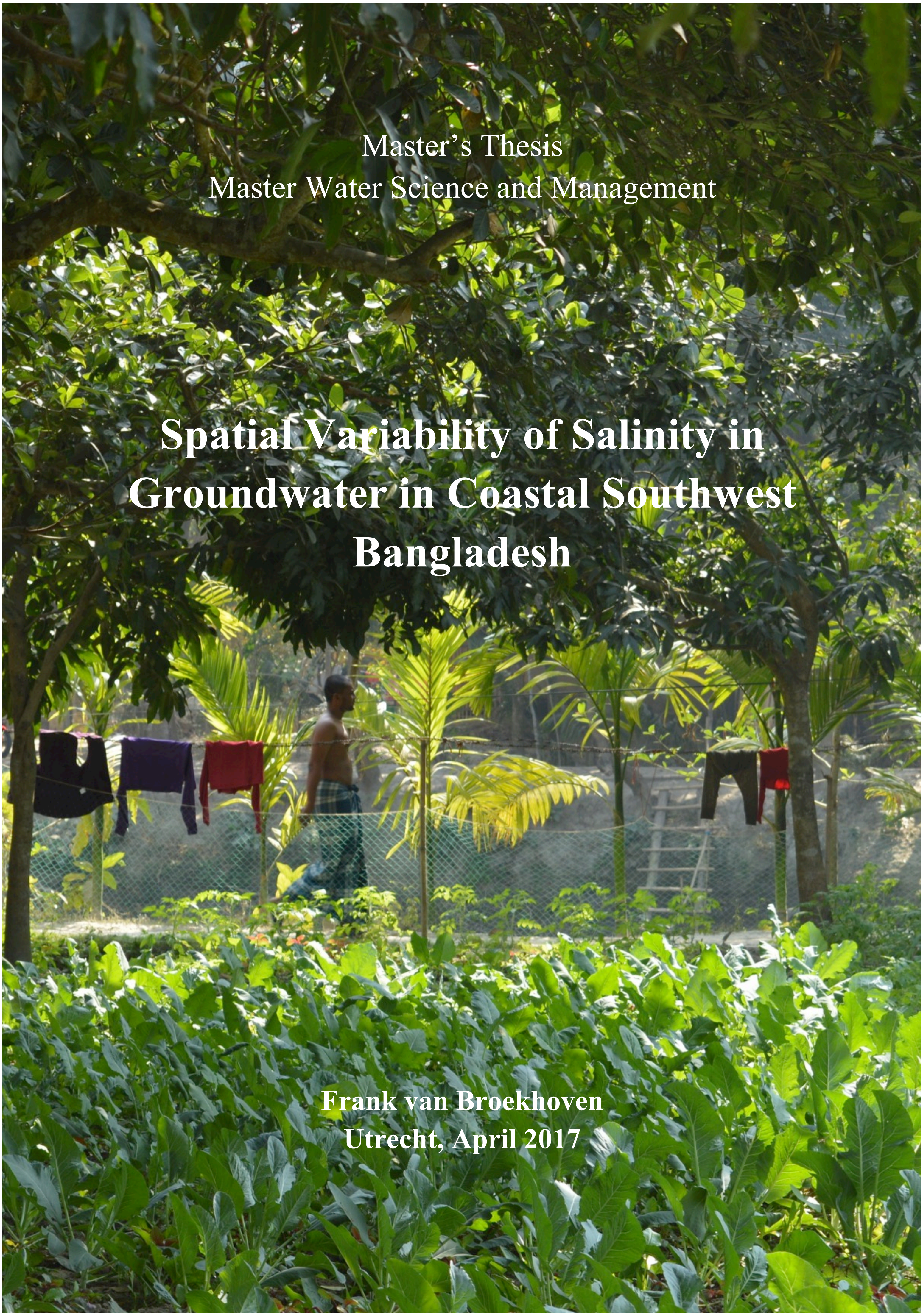

Master's Thesis
Master Water Science and Management

Spatial Variability of Salinity in Groundwater in Coastal Southwest Bangladesh

Frank van Broekhoven
Utrecht, April 2017

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Summary

Acacia Water and Dhaka University came up with Managed Aquifer Recharge (MAR) in order to relieve the freshwater shortage problem during the dry season in the coastal area of Southwest Bangladesh. The performance of these MAR-systems depends on hydrogeological conditions including salinity of the groundwater. Therefore freshwater lenses in the groundwater are critical for efficient use of MAR-systems.

The shallow groundwater of the coastal regions is primarily brackish with lenses of fresher water and the spatial variability of salinity in the groundwater is assumed to be very high. Because of the very high spatial variability of salinity in the groundwater this study focuses on the small-scale variability of salinity in the groundwater because a more detailed picture of the spatial variability was needed to understand the processes that cause this variability. The elevated area in Assasuni has been chosen as study area because there is a gradient in elevation and salinity present. The research objective of this study was to map the spatial variability of the salinity of the groundwater in on and around this elevated area of Assasuni and to find the factors that explain this spatial variability.

The research methods were divided into two parts. The first part was the fieldwork to map the spatial salinity distribution. The second part was the analysis of the data in form of a spatial analysis and a groundwater model to find the processes cause the formation of a freshwater lens in the groundwater.

The salinity measurements indicate a freshwater lens beneath the elevated area in Assasuni and more saline groundwater in the lower lying surrounding area. The formation of the freshwater lens can be explained by a difference in the salinity of the recharge. Which could be by either less saline flooding because of a difference in elevation or through difference in land use, by fresh ponds in the village on top of the elevated area and by brackish and saline inundation due to rice and shrimp cultivation at the surrounding area. It is unlikely that the variation in salinity of the groundwater is caused by differences in lithology. Another explanation that could explain the current distribution of saline groundwater are historical differences in depositional environment. This research gives some indications on what processes cause the variability of the groundwater in the southwestern coastal area of Bangladesh, but more research in needed to fully understand these processes.

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1. Introduction

1.1. BACKGROUND

Coastal deltas are some of the most densely populated places in the world and many of the world's megacities are located in these deltas. Deltas are dynamic natural and socioeconomic environments that have rich environmental resources and high economic potential but are also sensitive to the effects of urbanization, natural disasters and sea level change. Coastal deltaic groundwater resources are often vulnerable to degradation from seawater intrusion or through interaction with saline paleo waters, this is augmented by the increased stress on fresh water. This leads to salinization of surface waters and shallow fresh groundwater bodies which makes the water unfit for irrigation, drinking water supply or industrial purposes. Where the supply of freshwater is not adequate, the forced consumption of saline water can impact health by promoting the development of renal failure, kidney disease, hypertension and gastrointestinal irritation (Worland et al., 2015; Delta Alliance, 2016a; De Louw et al., 2011).

This study is on the Ganges-Brahmaputra-Meghna (GBM) Delta in Bangladesh, the largest and most densely populated delta system in the world with 130 million inhabitants (1300 inh/km2). The delta consists of a distinct landscape of a crisscrossed network of rivers estuaries together with extensive floodplains and wetlands. The GBM Delta is located in the tropical wet climate zone, it receives between 1500 and 2000 mm of precipitation each year in the western part and 2000-3000 mm in the eastern part. Most (82%) of the precipitation falls during the monsoon (June-October) (Delta Alliance, 2016b; Mukherjee, 2009). This rainwater combined with high discharges from the Ganges and Brahmaputra rivers provide sufficient freshwaters for a productive agriculture in coastal Bangladesh and it makes the delta one of the most fertile regions in the world. The Delta sustains besides agriculture, also the single largest mangrove forest in the world: The Sundarbans (Islam et al., 2015; Worland et al., 2015; Allison et al., 2003).

The GBM Delta has a great risk of flooding, several floods occur each year both riverine and coastal (Auerbach et al., 2015). During the wet seasons there is more than enough fresh water to supply drinking water to rural households. Nevertheless drinking water shortages are common during the dry season in the coastal areas. In the dry season the fresh-salt water interface moves upward in the rivers and consequently a large part of surface water becomes saline or brackish and thus unfit for potable and irrigation purposes (Acacia Water, 2015). The Ganges-Brahmaputra-Meghna Delta is particularly vulnerable because 20 million coastal inhabitants are directly affected by saline drinking water (Worland et al., 2015).

Climate change is expected to increase the salinity problems in the coastal area of Bangladesh because of a rising sea level. But also because prolongation of the dry season would reduce the availability of both fresh surface and shallow groundwater which increases the freshwater shortages (Acacia Water, 2015). Besides, a sea level rise would increase the seepage and salt loads into surface waters and thus enhance the shortage (De Louw et al., 2011).

In order to relieve the freshwater shortage problem, UNICEF asked Dhaka University and a Dutch consultancy firm (Acacia Water) to find a solution for the Southwestern part of Bangladesh. The study area borders the Sundarbans to the North and encompasses three districts: Satkhira, Khulna and Bagerhat (see figure 1.1) where the local economy is based on rice cultivations and shrimp aquaculture (Worland et al., 2015). Acacia Water and Dhaka University came up with Managed Aquifer Recharge (MAR). MAR has an enormous potential for sustainable water provision in poor delta communities. The MAR-systems installed in Southwest Bangladesh infiltrate fresh rainwater during the wet season below an impermeable clayey layer into a salt-water aquifer. The freshwater stays in the aquifer in the form of a bubble. This freshwater can be pumped up during the dry season and can be used as drinking water and irrigation water. See figure 1.1 for an illustration of the working of the MAR system in Southwest Bangladesh. The storage in the subsurface has an additional advantage; the water is purified by the soil and is therefore cleaner. Another advantage is that the freshwater bubble is protected against floods and the effects of cyclones, which threaten the region yearly. In 2009 a pilot study has been conducted in the region that focused on the technical, physical and hydrogeological boundary conditions for the performance the MAR-systems. 20 pilot locations have been tested and were considered successful. Therefore in 2013 another 73 test locations were added in the districts of Khulna, Bagerhat and Shatkira (Acacia Water, 2015; NWO, 2016).

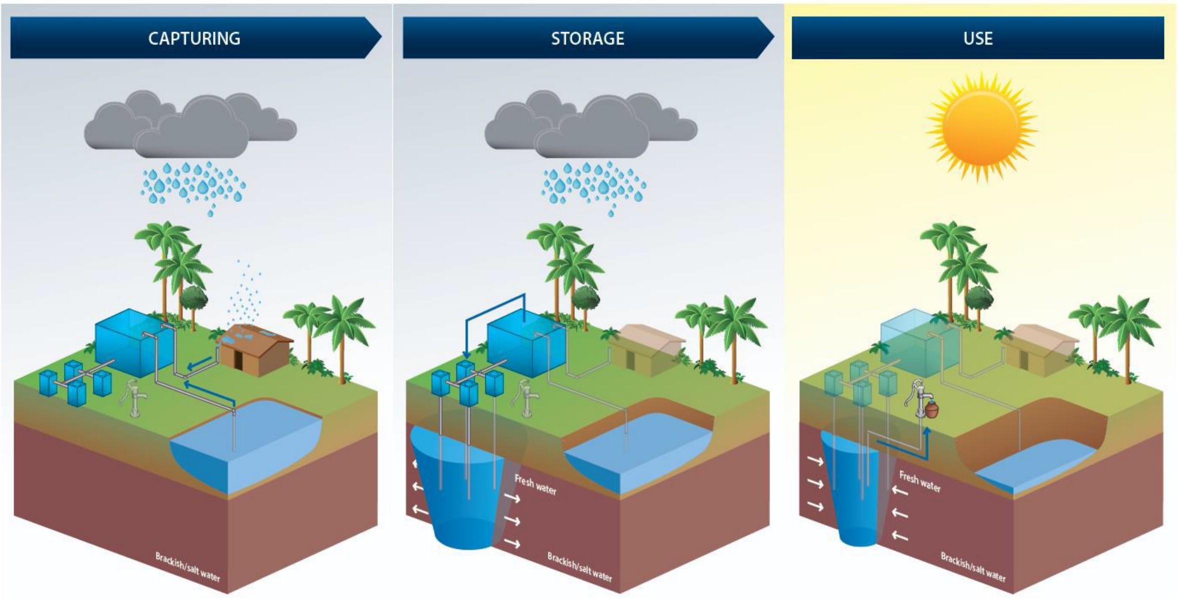


Figure 1.1: Illustration of the functioning of the MAR-system in Southwestern Bangladesh. Source: (Acacia Water & Dhaka University, 2015a).

1.2. PROBLEM DEFINTION AND RESEARCH OBJECTIVE

Some of the test locations of the MAR-systems are more efficient than others, which suggests knowledge gaps related to design, operation, water quality, governance and business development (NWO, 2016). Utrecht University, Delft University of Technology and Dhaka University formulated a research proposal to elaborate the study of Dhaka University and Acacia Water, this was granted by The Netherlands Organization for Scientific Research (NWO) and named the DeltaMAR project. The DeltaMAR project aims to enhance knowledge on financial, institutional, environmental, technical, and social factors that influence the potential of Managed Aquifer Recharge (MAR) for safe drinking water provision in saline deltas to contribute to a sustainable drinking water supply for many poor delta communities. This because the knowledge gathered during this project can also be used to successfully implement MAR-systems elsewhere (NWO, 2016; Future Deltas, 2016). The DeltaMAR project tries to close the knowledge gaps related to sustainable implementation of MAR-systems in terms of environmental and technical prerequisites. In the DeltaMAR project are four PhD candidates involved, each with their own specialization: 1) Quantity, 2) Quality, 3) Governance and 4) Synthesis (figure 1.2). So both the socio-economic and technical aspects about the functioning of the MAR systems are being investigated. This Master's Thesis is part of the synthesis research (PhD research of Floris Naus) about the development of an a priori evaluation method for MAR performance in saline deltas, based on integration of hydrogeological and socio-economic parameters (NWO, 2016; Future Deltas, 2016; Acacia Water, 2015).

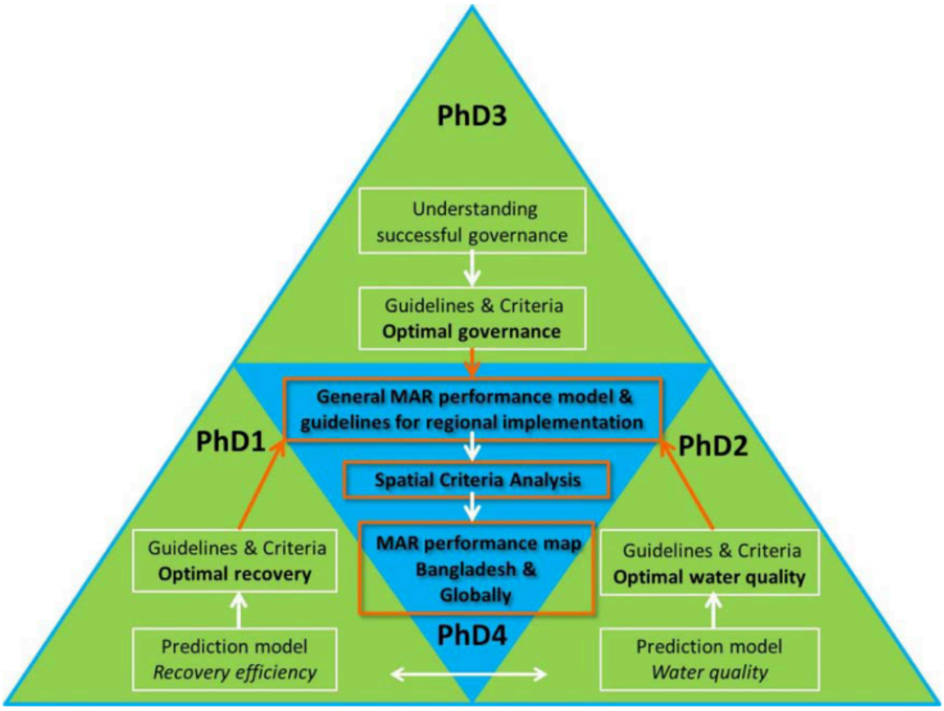


Figure 1.2: Research overview of the four PhD candidates for the DeltaMAR project (NWO, 2016)

More knowledge about the hydrogeological conditions in Bangladesh is required for optimal MAR performance, because in general MAR-system performances are less in saline conditions. Salinity affect the successful implementation of the MAR-systems due to density difference driving forces (buoyancy forces) (Hendriks, 2010; Dingman, 1994) and salinization processes (Fitts, 2002). Therefore fresh water lenses in the groundwater are critical for efficient use of MAR-systems.

The shallow groundwater of the coastal regions is primarily brackish with lenses of fresher water (Worland et al., 2015; Ayers et al., 2016). The basin is often treated as homogenous and isotropic but according to Worland et al. (2015) it is best described as zonally homogenous, vertically anisotropic, and partitioned by hydrogeologic properties that describe the heterogeneity of each region. The hydrogeological system of the study area is simply represented by a three aquifer system consisting of a semi confined, shallow aquifer formed in the Holocene extending 100 m below ground level. Which is made up primarily of sand overlain by heterogeneous and variably thick confining layer of poorly developed immature silt and clay. The shallow aquifer is underlain by two distinct aquifers dominated by sandy sediments deposited since the Pleistocene and which are vertically separated by Pleistocene muds extending 200 and 300 m below ground level (Worland et al., 2015). The groundwater flow of the shallow aquifer is constrained by local topographic conditions and flows over a distance of a few kilometers and several meters to tens of meters deep (Worland et al., 2015).

According to Ayers et al. (2016) the distribution of salinity in one of the polders (Polder 32) in the region is best described as random, due to the very high variability in salinity. Besides the spatial variability of salinity in the region is the result of limited mixing and low and spatially variable recharge rates and flow velocities. According to Worland et al. (2015) the salinity of the groundwater is the result of complex land building processes during the last 10,000 year and reflects the bulk of the groundwater the quality of the depositional environment at the time deposition, which causes the groundwater to be mainly brackish. The freshwater lenses are expected to originate due to recent infiltration of rainwater, however conclusive processes that causes this infiltration are not yet determined. So far, the current knowledge about the processes that causes the variations of salinity in the groundwater cannot fully explain the high spatial variability of salinity in the groundwater.

Because of the very high spatial variability of salinity in the groundwater this study focusses on the small scale variability of salinity in the groundwater because a finer picture of the exact spatial variability is needed to understand the processes that cause this variability.

Floris Naus has conducted regionally meassurements of salinity of the groundwater, this data showed a gradient in elevation and salinity is present at Assasuni. Therefore it has been chosen to conduct the small scale research at this location. Fresher groundwater was measured on top of the elevated area and more saline in the lower lying surrounding area (figure 1.3). The study area lies in Southwestern part of Bangladesh, North of the Sundarbans, and the local economy is based on rice cultivations and shrimp aquaculture (Worland et al., 2015). In figure 1.4 can be seen that the elevated area is higher than the surrounding area but not very clearly, however in the field it is clear that the area is more elevated than the surrounding area. Figure 1.5 shows the soil map of the study area which shows that the elevated area is formed by riverine deposits and the surrounding area by tidal flat deposits. In the middle of the elevated area in East-West direction is an 'old creek' visible. Currently it is an incision of the elevated area where there is cultivation of rice paddies. Based on the stories of the local population it can be assumed that it was a tidal creek until recently.

The research objective of this study is to understand the underlying hydrological processes that cause the spatial variability of salinity at elevated areas in Southwest Bangladesh. This is done by mapping the spatial variability of the salinity of the groundwater on and around the elevated area of Assasuni and by investigating what factors influence the interaction between the groundwater and the surface water around elevated areas in order to explain the current spatial variability. Therefore this study focuses on the geohydrological system of the elevated area in Assasuni.

1.3. RESEARCH QUESTIONS

The following research question and sub questions were formulated:

How can the local variability of salinity on and around the elevated area in Assasuni, Bangladesh, be explained?

1. *What is the local variability of salinity of the groundwater on and around the elevated area in Assauni?*
2. *What is the local lithology of the subsurface on and around the elevated area in Assasuni*
3. *What factors may explain the freshwater lens in the shallow aquifer beneath the elevated area in Assasuni?*

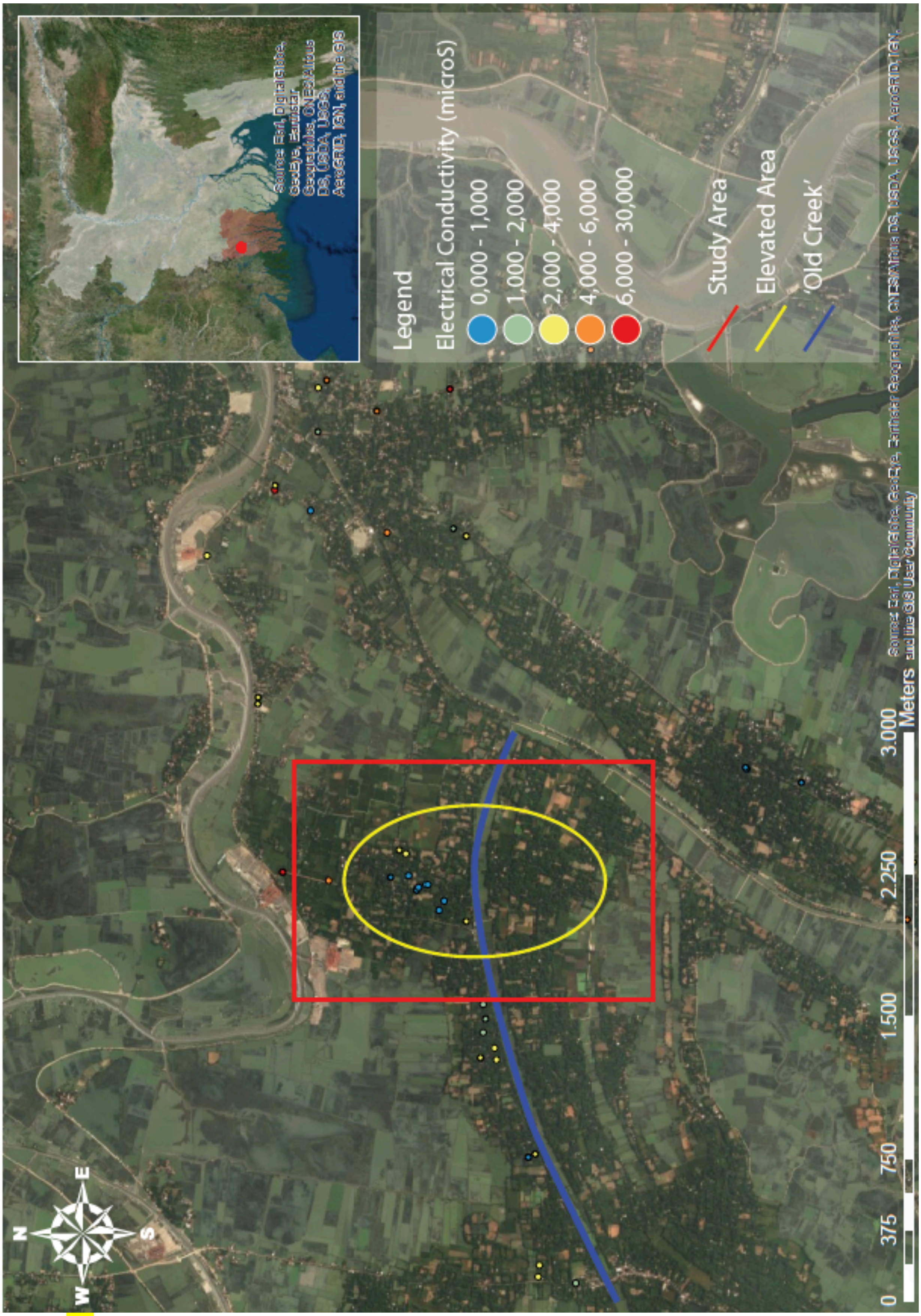
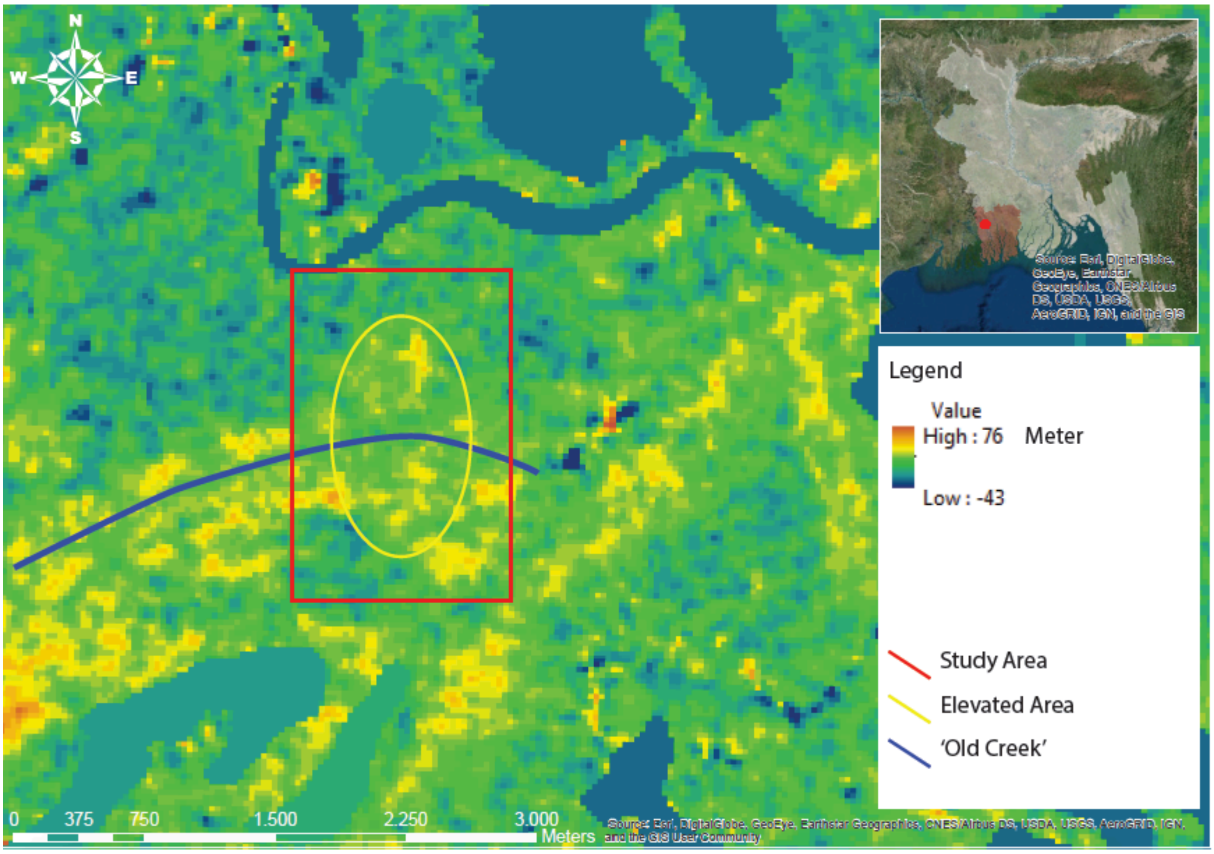
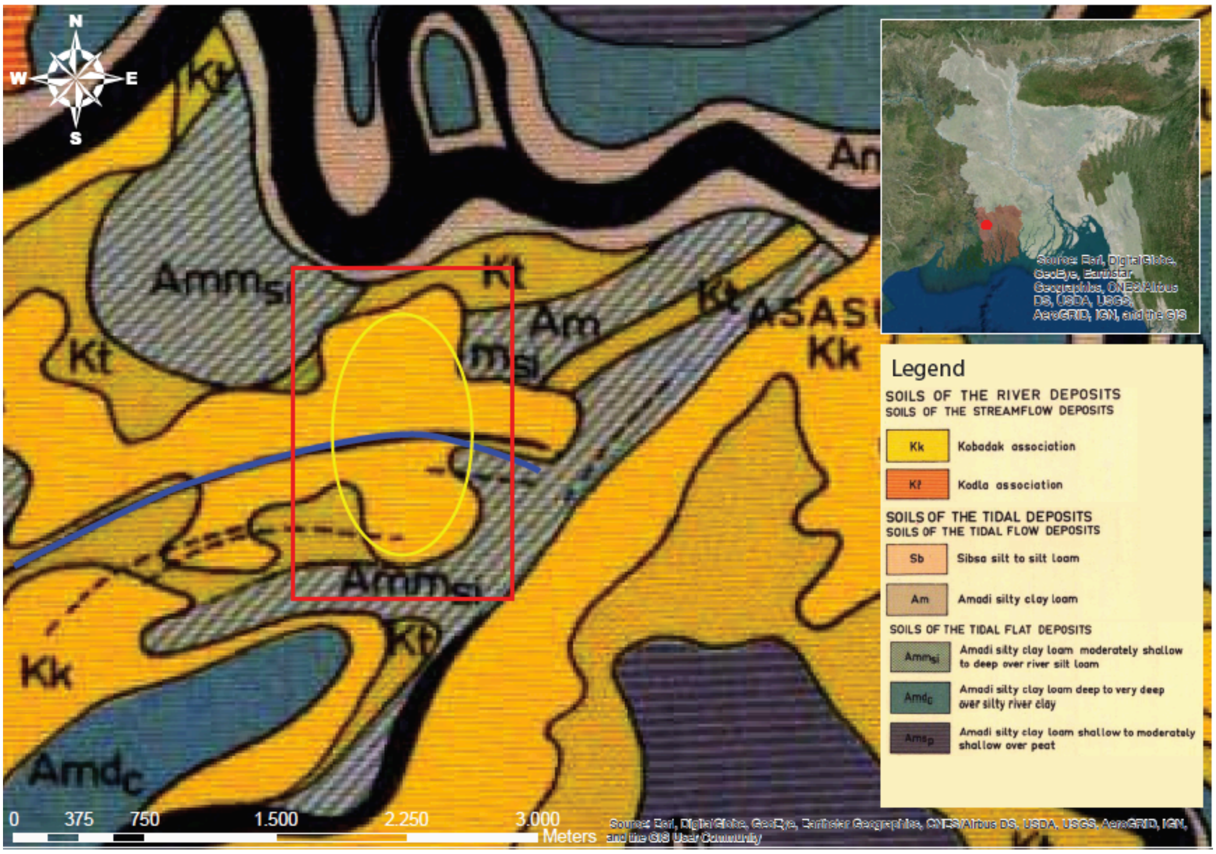


Figure 1.3: OMSCHRIJVING. Source: basemap of ESRI ArcGIS.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 1.4: Elevation map of the study area in Assasuni. Source: Shuttle Radar Topography Mission (SRTM).



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 1.5: Soil map of the study area in Assasuni. Source: FAO, 1959.

1.4. HYPOTHESES

According to Ayers et al. (2016) and Worland et al. (2015) the high spatial variability of salinity in the region is the result of limited mixing, low and spatially variable recharge rates and flow velocities. Four hypotheses were formulated to explain the variability in salinity: 1) difference in elevation, 2) difference in land use, 3) difference in lithology and 4) difference in depositional environments. The first three hypotheses assume variability because of differences in recharge, the last hypothesis assumes differences in depositional environments during the build up of the sediments.

Hypothesis 1: differences in elevation. A possible factor that could explain the salinity variation in certain places is difference in elevation. Local topographic conditions on a small scale, like small differences in elevation, might cause the formation of fresh water lenses (Worland et al., 2015, Pauw et al., 2015). The polders in the Southwestern region of Bangladesh have no significant local topography and an average vertical relief of nearly zero, but there are minor micro-level topographical differences (Worland et al., 2015).

According to De Louw et al. (2011), formal tidal creeks, in the province of Zeeland, the Netherlands, subside less than the surrounding area and are therefore higher. This causes induced infiltration of freshwater and thus the formation of a freshwater lens beneath the elevated area. Besides the elevated get less inundated with brackish or saline water during marine floods, due to elevation difference. Therefore the hypothesis is that there will be a fresh water lens below areas with a small increase in elevation.

Hypothesis 2: differences in land use. The land use on the elevated area is different than the surrounding area. A village is located on top of the elevated area. There are freshwater ponds in this village, which could lead to an increase of fresh recharge underneath the elevated area (Ayers et al., 2016). The surrounding area has brackish and saline inundation during the year, because the rice fields are inundated with brackish water and there are saline shrimp farms. Shrimp farming causes the surface water to salinize which indirectly contaminates the groundwater with saline water. Besides tubewells lower the groundwater level which can cause induced infiltration of salt water from shrimp farms (Paul & Vogl, 2011). Due to this difference in land use, the salinity of the recharge can also differ between the elevated and surrounding area.

Hypothesis 3: differences in thickness of the clay cover. According to Worland et al. (2015) and Ayers et al. (2016) the confining clay layer varies in thickness and at places where the confining clay layer is thinner it would allow vertical infiltration of rainwater. Therefore the hypothesis is that the clay cover is less thick at the elevated area and that this causes fresher recharge and thus a fresh water lens beneath the elevated area.

Hypothesis 4: differences in depositional environment. According to Worland et al. (2015) the bulk of the water in the aquifer connate and reflects the water quality of the deposition environment in time of deposition, because the flow velocities are considered very low. Deltas are complex and host many different sedimentary environments, like swamps, channels and floodplains. A change in sea-level might cause a change the position of these different sedimentary environments to move inshore or offshore with time (Marshak, 2015). According to Delsman et al. (2014), coastal groundwater reserves reflect a complex evolution of marine transgressions and regressions and are rarely in equilibrium with current boundary conditions. Therefore the complex evolution history is key in understanding the present-day variability.

The Bengal Basin has gradually been filled by alluvial sediment washed down from the highlands of the Himalayas and formed a low-lying flat delta during the last 11.000 years (Islam et al., 2015). During the Pleistocene a big channel deposited sand in the study area and during the Holocene it is expected that the river channels came more under influence of marine salinity due to sealevel rise. The sedimentation started at the western part of the delta and then gradually migrates eastwards (Mukherjee et al., 2009). Due to this migration, less sand is deposited at the study area and most of the study area transformed into floodplains. Mainly clays and silts are deposited from this period onwards. This results in a confining clay cover in the southwest coastal region (Mukherjee et al., 2009; Allison et al., 2003). The soil of the Holocene sediments is visible in the regional soil map by the FAO (1959) (figure 1.5). According to the map, the elevated area in Assasuni is of fluvial silts and the surrounding lower lying area of tidal flat clays. Therefor the hypothesis is that the differences in salinity are caused by differences in depositional environment. It could be that the fresh groundwater is caused by riverine deposits (fresh) and that the saline groundwater is caused by tidal deposits. The differences in salinity could therefore be old and stable because the thick confining clay layer slowed the hydrological system drastically and is therefore stable.

2. Methods

The research methods are divided into two parts. The first part is the fieldwork to collect data about important parameters of the salinity distribution. The second part is the analysis of the data in form of a spatial analysis and with a groundwater model. See figure 2.1 for a schematization of the methods. The setup of the methods for the fieldwork is based on the setup created by Floris Naus, MSc (2016) for his PhD research.

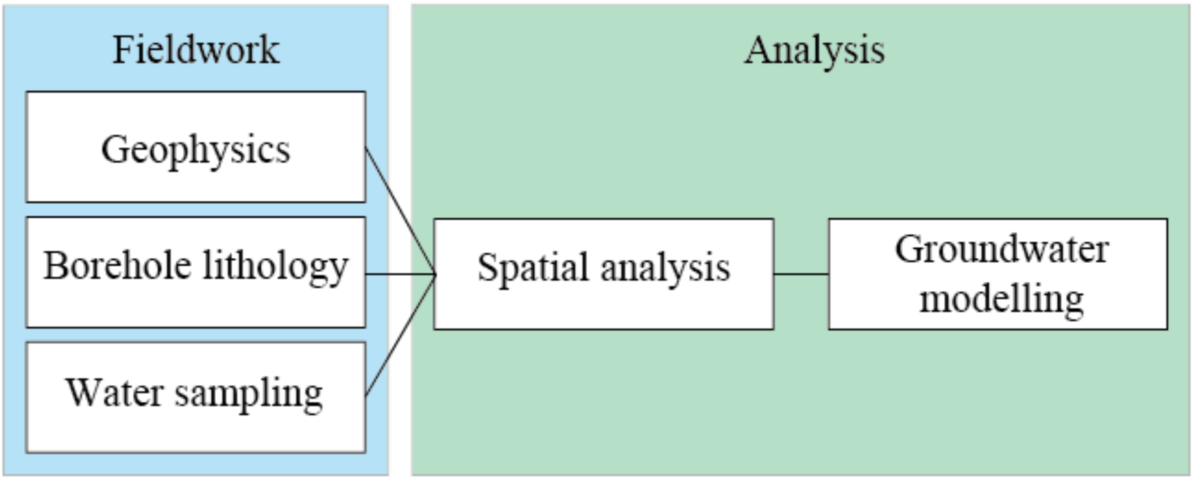


Figure 2.1: Schematization of the methods, fieldwork and analysis.

2.1 FIELDWORK

The data collected during fieldwork is visualized to map the local variability of salinity in the groundwater on and around the elevated area in the research area of around Assasuni. The local variability of salinity in the groundwater has been determined by using geophysics (electrical sounding: VES and profiling), water quality sampling of wells and installing piezometers. With electrical sounding the variability in resistivity has been determined vertically by using vertical electrical sounding and horizontally by using horizontal profiling. Next, to measure the water quality also the lithology and groundwater levels have been determined. The lithology has been determined by analyzing the boreholes made for the piezometer and hand drillings. The water level has been determined in the piezometers. Besides, maps and cross-sections have been made and analyzed to see if there are relationships between the spatial variability of salinity and hydrogeological conditions, like geology, lithology, water levels (direction of flow) and water quality (chemical properties). The salinity variation has been interpreted by analyzing if there is variation between elevation, depth, lithology, height of the water table, and flow directions.

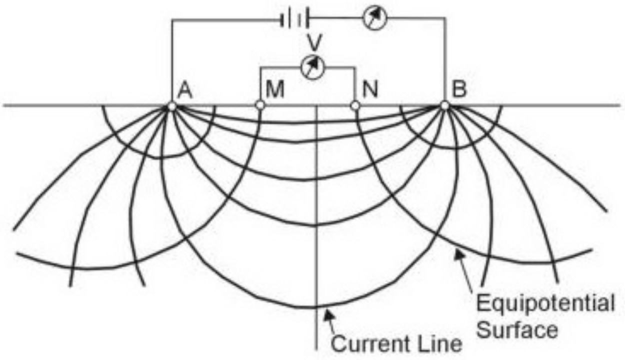
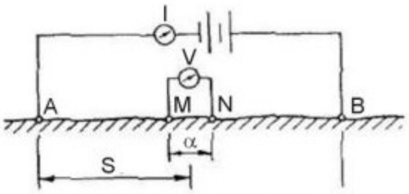


Figure 2.2. Equipotentials and current lines on a homogeneous subsurface. Source: EPA, 2016.

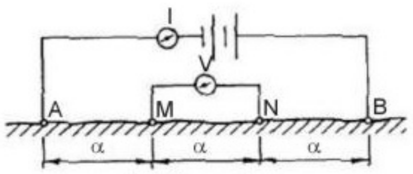
2.1.1. SURFACE GEOPHYSICS

In the elevated area the distribution of fresh and saline groundwater and lithology have been measured by using Vertical Electrical Sounding (VES). VES is an applied geophysics method and it is in particular an Electrical Resistivity Method. Geophysics studies the subsurface by means of physical measurements on the ground surface and it is widely used since the 1970's. The Electrical resistivity methods are a good way to map and monitor groundwater sources (Shendi, 2008; Reynolds, 2011). Electrical resistivity methods are based on the principle that the distribution of electrical potential in the ground around a current-carrying electrode depends on the electrical resistivity and distribution of the surrounding soil. The combined effects of the lithology and the water salinity determine the resistivity. The resistivity is determined by applying an electrical direct current (I) between two electrodes implanted in the ground and to measure the difference of potential (V) between two additional electrodes that do not carry current (figure 2.3) (EPA, 2016).

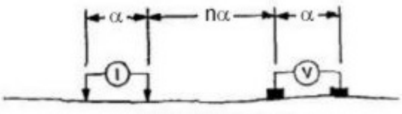
By using Ohm's law the resistivity can be determined. Ohm's law states that resistance R=V/I. Besides this, resistance is proportional to length (L) divided by area (A) and can be written as $R = \rho\frac{L}{A}$. Where ρ is the true resistivity and ρ can thus be written as $\rho = \frac{VA}{IL}$ (Reynolds, 2011). In sedimentary layers the resistivity of the interstitial fluid is sometimes more important in determining the resistivity of the soil. Archie's law gives this relation: $\rho = a\varphi^{-m}s^{-n}\rho_w$. With ρ_w the resistivity of the pore water, φ the porosity, s the volume of fraction of pores with water, a, m and n are constants. (Reynolds, 2011). The true resistivity can easily be determined in this way for a homogeneous subsurface. However in reality the subsurface is heterogeneous with various lithological and water quality differences in it. Therefore the apparent resistivity (ρ_a) has been measured during field experiments (Reynolds, 2011; EPA, 2016). To measure the resistivity of the subsurface the length and area of the current lines are needed between the electrodes and those depend on the setup of the electrodes. There are three main electrode configurations: Wenner, Schlumberger and dipole-dipole (figure 2.4) (Shendi, 2008).



a. Schlumberger Array



b. Wenner Array



c. Dipole - Dipole Array

Figure 2.3: Electrode array configurations. Source: EPA, 2016.

In order to determine the vertical changes in resistivity, the distance between the electrode array is varied: the greater the distance, the greater the depth of measurement. In this way the apparent resistivity against electrode spacing can be used to indicate vertical variations in resistivity (EPA, 2016). The Schlumberger array configuration is the easiest to use in the field to determine the vertical changes in resistivity because then, only the outer current electrodes have to be moved in various distances and the inner potential electrodes can remain in the same position (Reynolds, 2011). Therefore the Schlumberger configuration has been used in the fieldwork for vertical sounding.

For horizontal profiling or constant separation traversing (CST) the electrode array with constant spacing can be used to determine lateral changes in apparent resistivity, which reflect lateral geologic variability (EPA, 2016). The Wenner Array is best used for this in the field because the electrodes are positioned in a constant distance. Therefore, when moving in a lateral way only one electrode has to be moved (Reynolds, 2011).

The electrical resistivity method has some limitations that affect the accuracy and resolution. The resistivity is determined by the combined effects of the lithology and the water salinity. This makes the interpretation of the resistivity more complex. Besides, the measured value obtained at any location represents a weighted average of the effects produced over a large volume of the subsurface where the nearby soil layers contribute the most. This results in smooth curves where the differences in resistivity must be derived from. This makes that only rough estimates can be made of the subsurface (EPA, 2016). With the help of the supporting software (SchlumBG for Windows) an indication can be made of several layers with different resistivities that would give the found resistivity curve.

Besides the use of the VES, also boreholes have been made with the help of a hand auger with a depth of min 2m to max 6m. These boreholes have been investigated in order to map the sediments of the subsurface (lithology). The lithology has been used together with VES in order to get a more accurate image of the subsurface. The lithology helps with the interpretation of the resistance in the subsurface.

The electrical sounding measurements in the field have been done with the ABEM SAS1000 Terrameter, which was borrowed from the DPHE. The setup used in the field is shown in the photo's underneath. The locations to do the VES have been chosen based on enough space to do the measurements because it requires a lot of room to go deep. The length of the outer electrodes is six times the depth of measurement (Reynolds, 2011). This was easy in the rice fields surrounding the elevated area but more difficult on top of the elevated area where the village is, because there were several obstacles like houses and ponds in the way. The same is true for the profiling because a straight transect is needed to do the profiling without many obstacles and ponds that would influence the measurements. Therefore the locations for profiling have been chosen based on if there would be enough space for the measurements.

2.1.2. HAND DRILLINGS

In this research hand drillings were done to determine the lithology of the shallow subsurface. The shallow boreholes have been made by an hand auger. The unsaturated part has been done with and Edelman hand auger while the deeper and saturated part beneath the groundwater table has been drilled with a gouge. The gouge makes soil samples of 60 centimeters and makes sure that the soil stays intact for better observations of the layers. The soil samples were placed next to the borehole and a measuring tape to get a good overview of the soil. The features were written down for each 10 cm, like color, texture, soil type and organic material.

Besides the lithology, also water samples have been taken to identify the groundwater quality. The first sample was taken when the groundwater table was reached while the second sample was taken at the deepest point. The first sample is only the top layer of the groundwater but the deeper sample is a mix of the water from the whole borehole.

2.1.3. PIEZOMETERS

In order to determine the lithology of the deeper subsurface, to measure groundwater levels and to measure the salinity, a transect of boreholes with piezometers was installed across the elevated area in Assasuni. The exact location of the nested has been determined by locations where changes were visible in the VES and where it was able to place a piezometer with the approval of the local people. The cross-section goes from North to South.

The boreholes are 150 feet (around 46m) deep and have been drilled by 3 teams of local workers. They drilled the holes by making a bamboo pole construction to make a lever to shake a tube in to the ground in a small pond of water. The lever with one worker lets the tube go up and down in the ground while another worker places his hand on top of the pole. When the tube goes up the hand closes the tube to make a vacuum and when the tube goes down the hand is removed to let the sediment and drilling fluid out of the tube (figure 2.4). The pond water acts as drilling fluid. The method of drilling is widely used in Bangladesh and is further described in Radloff et al., (2015) and Horneman et al., (2004). Every 5 feet (around 1,5m) a sediment sample has been taken by collecting them from the tube in a bucket and placed on a sheet for further inspection. The sediment samples were examined by the researchers of the project (author, Floris Naus and Rebecca van Weesep) for grain size, soil type, color, organic matter, oxidation marks and layering of the soil.

When the drill team reached 150 feet a piezometer has been placed. At some locations there are nested piezometers placed with three piezometers close by each other. The placing of the piezometer was done by first, closing the bottom of the filter. Then it was placed at a depth dependent on the lithology and how many piezometers were placed in the nest. In general is the most shallow possible depth (10-15m) taken just beneath the confining clay layer and then around 20-25m and another one at 35-40m. Sand and gravel are placed around the filter to prevent the filter from clogging. After the piezometer is installed it gets pumped with a hand pump for 30 minutes to make sure that the drilling fluid is flushed away and only the correct groundwater is pumped up by the filter of the piezometer. After at least a day , the water sample from the piezometers have been taken. This to settle the water in the piezometer to make sure the water level was steady. The water levels of the different nested piezometers have been measured with a digital measuring tape. The relative height of the surface level was measured by a technical team using a digital leveler and a levelling staff. Subsequently, the relative heights of the water levels in the piezometers were determined of the piezometers top and the ground level. This is done in order to compare the different heads in the piezometers. In some piezometers divers are inserted to monitor the water level. Divers are water pressure meters that determine the water level continuously by converting the pressure in to the height of the water level.

In total 25 piezometers have been placed across the elevated area on 13 locations in a transect from North to South. The piezometers are placed in nests of 3 piezometers (4 locations) nests of 2 piezometers (4 locations) or as a single piezometer (5 locations). The locations of the (nested)piezometers were chosen to get measurements across the cross-section as well as in the lower lying area next to the elevated area, where almost no tube wells are located. The depth of the piezometer filters varies between 6m and 46m. The depth and the locations of the piezometers were chosen to be at places where no near measurements are taken in the aquifer, like the very shallow part just beneath the confining clay layer and the deeper spots. This, together with the other measurements, gives a full overview of the electrical conductivity of the groundwater along the cross-section.

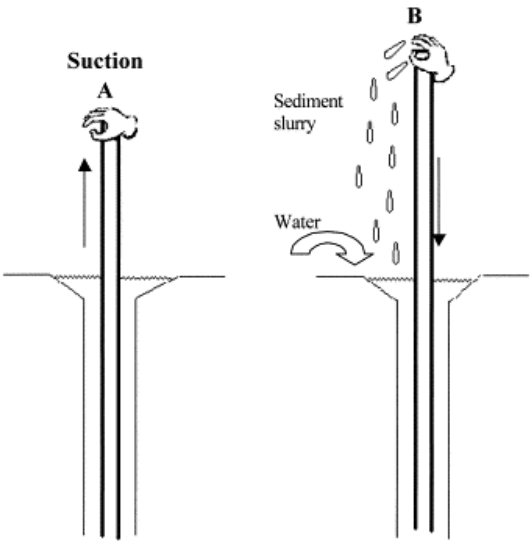


Figure 2.4: Illustration of the drilling method, (Horneman et al., 2004)

2.1.4. WATER SAMPLING AND DETERMINING THE WATER QUALITY

The water quality of the piezometers, boreholes, ponds and tube wells has been measured in the field and sampled for further analysis. Tube wells are located across the whole village for drinking purposes of the local population. A large part of the houses have a personal tube well on their property next to their homes. Before the tube wells and piezometers were measured and sampled the well has been pumped around 5 minutes to flush the stagnant water. This was done in order to make sure that the well water is equal to the surrounding groundwater and is not influenced by the stagnant water in the borehole. The electrical conductivity (EC), temperature and pH have been measured in the field by a multimeter. The measuring probe has been thoroughly rinsed before measuring each sample. The electrical conductivity is the most important parameter because it directly related to the salinity of the water. The depth of the tube well has been estimated by asking the owner of the tube well and the location has been noted down from a GPS device. Besides the depth and the location also other relevant attributes have been noted like the distance to a nearby pond. In the area on and around the elevated area in Assasuni water samples have been taken from 120 tube wells and also the electrical conductivity (EC) was measured. The tube wells are selected to create a balanced distribution of measurements from North to South and from East to West.

The water has been sampled for a brief quality analyses in Bangladesh and a more extended analysis in the Netherlands. The analysis in Bangladesh consists of measuring the Arsenic concentration, nitrate concentration and the alkalinity (HC03- concentration). This has been done within 48hours after sampling at the office of the DeltaMAR project, because it has to be done quickly so the HCO3- concentration doesn't change due to contact to with CO2 in the air. The alkalinity has been tested with an alkalinity titration kit of Hach, and the arsenic concentration with a arsenic titration kit of Hach. The nitrate concentration has been determined by placing indication strips in the water.

The water sample for analysis in the Netherlands has been filtered through a 0.45 micrometer membrane using a syringe and stored in a 15ml vials. This has been done to exclude suspended matter in the water which may distort the measurement. The lab analysis in the Netherlands consisted of ion chromatography (IC) and inductively coupled plasma mass spectrometry (ICP-MS). These methods give a broad overview of the contents (cations and anions) of the water. The results of the IC and ICP-MS were delayed and are therefore have not been analyzed at the moment of writing.

2.2 MODELING

2.2.1. MODEL DESCRIPTION

A indicative groundwater model has been used to simulate the water level and salinity distribution in order to understand the processes that cause the variation. The geohydrological model MODFLOW with SEAWAT extension is a density dependent groundwater flow model, with coupled solute transport. Because of the density dependent flow, the model is suitable to model groundwater flow in coastal aquifers with the interaction between fresh and saline groundwater. MODFLOW with SEAWAT extension is a 3 dimensional model, but it in this research it has been used in a 2 dimensional manner to simulate a cross-section across the elevated area in Assasuni. The model simulates 1) groundwater flow (MODFLOW), 2) solute transport and 3) density dependent flow (SEAWAT) (USGS, 2016). The SEAWAT code models coupled variable-density flow and solute transport. The flow and transport processes have been computed by MODFLOW and MT3DMS that are incorporated in SEAWAT. The shell program is Processing Modflow (PMwin). This chapter describes the setup of the model used in this research.

2.2.2. MODEL SETUP AND HYDRAULIC PARAMETERS

Grid size: The setup for the model is a cross-section across the elevated area from the river on the northern side to the river on the southern side. The two rivers are around 3.5 km from each other. This has been measured with the ArcGIS measurement tool (figure 1.3 in introduction).

The grid of the model has been set up with 175 columns of 20m, 1 row of 200m and 55 layers of 2m. So the model is a cross-section of 175 by 55 cells with a length of 3500m and a depth of 110m. The depth is chosen to be 110m, because the depth of the first aquifer is 110m according to the regional borehole made by the DPHE in the study area. After 110m is there a thick clay layer. This clay layer is the bottom of the model and assumed as a no flow boundary. The width is chosen to be 200m because this is the area of the buffer around the cross-section.

Elevation: The surface of the model is at 0m, but the elevated area has a height of 1 and 1,7 m for the left part and height of 1 and 1,4 m for the right part. The middle part has also a height of 0m. These values are based on levelling measurements in the field, see figure 2.5 for a visualization.

Lithology: To simplify the model, it has been chosen to only use two different lithologies: sand and clay. The clay is on top and sand beneath. The thickness of the lithology is based on the field measurements, but lithology is simplified to get two distinct layers: an aquitard (clay) and an aquifer (sand). In reality the lithology is more complex and there are small pockets of clay in the aquifer. The clay layer is visualized in figure 2.5. The soil types are specified by different values for hydraulic conductivity and porosity.

The transmissivity (T) of the aquifer of the closest MAR site (1.6 km) has a value of 120m2/day and a thickness (d) of 10.67 m (Acacia Water & Dhaka University, 2015b). This gives a conductivity K= T/d = 120/10.67 = 11.25 m/day = 4106.25 m/year for sand. According to Hendriks (2010), the conductivity of clay varies between 0,0000001 and 0.2 m/day. For the vertical conductivity in the model the value of 0.001 m/day (0.365 m/year) is used.

Research has shown that porous aquifers are anisotropic which means that the horizontal conductivity is normally bigger than the vertical conduction and can differ substantially. This is due to depositional processes of laminations formed by clay minerals in sediments, which results in larger horizontal hydraulic conductivities (Chen, 2000). According to Bot (2011) the rule of thump is that the anisotropy is 1:10 for vertical and horizontal flow. So the horizontal conductivity is a factor 10 bigger than the vertical conductivity.

The porosity of clay varies between 0.4 and 0.7 and the porosity of sand varies between 0.25 and 0.4 (Hendriks, 2010). The effective porosity (n_e) is lower because not all pores participate in the water flow process, because there are dead-end pores (Hendriks, 2010). Therefore the effective porosity in the model is taken at the low end of the range. The values in the model for effective porosity are 0.4 for clay and 0.25 for sand.

Specific storage and specific Yield: Specific storage is defined as the volume fraction of water as unit volume of aquifer releases from storage because of expansion of the water and compression of the grains under a unit decline in head (Narasimhan, 1980). The value of 0.0001/m has been chosen for the specific storage, because it is assumed to be very small. Specific yield is defined as the volume of water per volume of porous medium that an unconfined aquifer releases from storage by the forces of gravity in response to a decline of the water table (Hendriks, 2010). The specific yield is usually equal or close to the effective porosity, therefore in this model it is equal to the effective porosity.

Salinity: The model uses only one species for salinity: Chloride concentration [Cl-/l]. Chloride concentration has been chosen as a reference concentration because it is the most contributing element in the salinity of seawater (Bot, 2011). Besides, chloride is also a conservative element, therefore it doesn't change due to internal factors. The slope that relates fluid density (rho) to solute concentration (C) is DRHODC ($\Lambda\rho/\Lambda C$) and has a value of 0.7. No kinetic reaction is assumed.

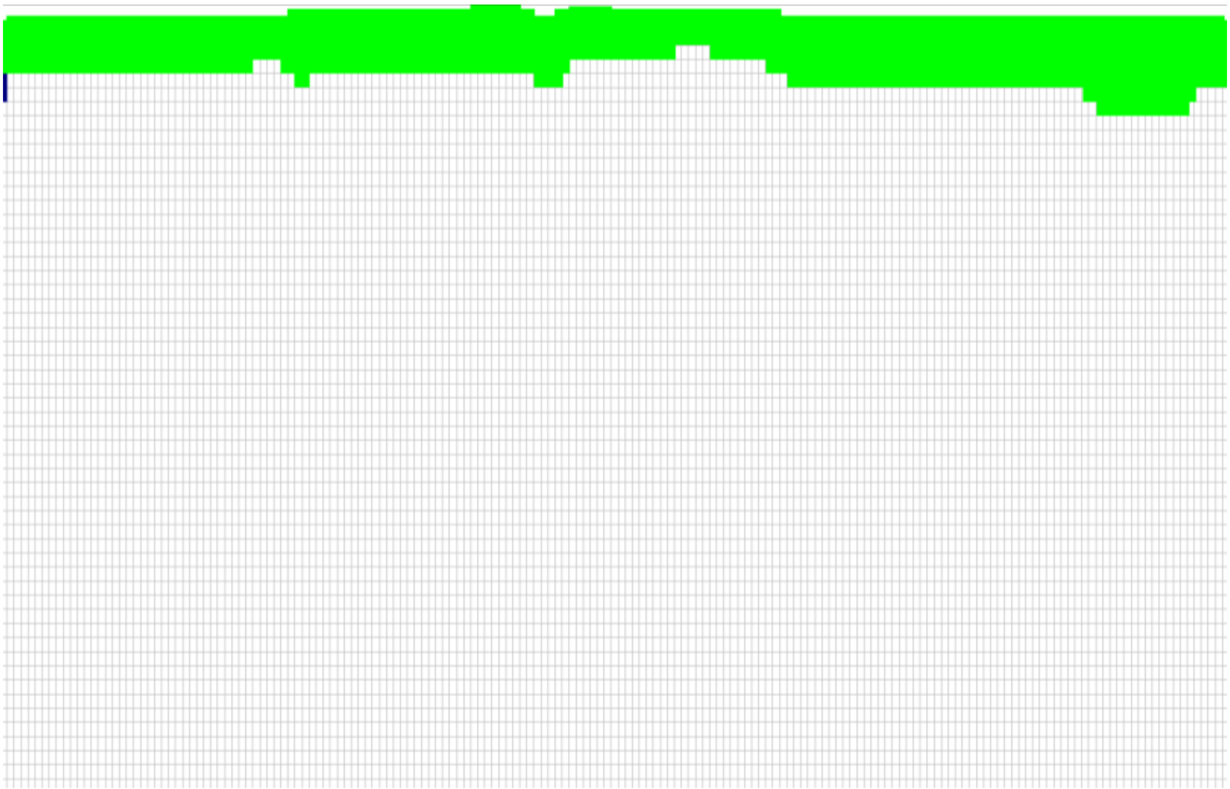


Figure 2.5: Layout of the model, 175 by 55 cells, top layer elevation and confining clay layer (green).

2.2.3. HYDRAULIC BOUNDARY CONDITIONS

Rivers: On both sides of the cross-section are rivers. The locations of the two rivers are no flow boundary conditions for the model because is it assumed there is no horizontal flow beneath the rivers. These rivers are considered as constant head cells and are assumed to be 10m deep. The rivers are simulated by constant head status (cell status = -1) with a head value of – 1.5 m, and are modelled in such a way that the groundwater flow corresponds with the field observations. This has the result that the northern (left) river is assumed to be in direct contact with the aquifer and that the southern (right) river is surrounded by clay. This causes most of the water to flow into the northern river. Which corresponds with the field observations, because the heads of the piezometers show a declining gradient from South (higher) to North (lower) and thus suggests a groundwater flow in northern (left) direction. The clay layer at 110m depth is the bottom of the model and assumed as a no flow boundary.

Recharge: In this model, recharge is simulated as the net recharge of the aquifer because evaporation is left out of it. The recharge is vertically assigned to the top layer cells of the model, which would simulate precipitation and inundation. The recharge is constant during a stress period but can be altered between stress periods. The input value for the recharge in this model is 0.025 m/year, because this value gave the most realistic head for the situation, based on error and trial in the model. The head varies from -0.7 to -1.5 m thus a total head gradient of 0.8m. The precipitation in the region is around 2.67 m/year (World Bank, 2017), so this would mean that the net recharge is only 0.96% of the yearly precipitation.

2.2.4. INITIAL CONDITIONS

Time: The model is divied into 6 stress periods with different length. The stressperiods are further divided into time steps. The conditions can be altered between different stress periods but are the same between time steps. The smaller the timesteps, the more accurate the model is. The length of the stress periods increaseses in time, from 1 year to 500 year . The stress periods are cumulative and result in the following times per result: 1, 10, 100, 250, 500, 1000 and 1500 years. This division has been chosen to observe the time scale of the processes happening in the model. The Transport stepsize is 1 year, for every year the concentrations are calculated. The model uses transient flow simulation therefore the flow conditons change during the model simulation.

Initial hydraulic head: The initial hydraulic head of the cells has been chosen to be -1m. A value close to the field observations and higher than the boundary cells of the river, which are set at -1.5m.

Salinity: The salinity value has been chosen to be 6.3 g/l (kg/m3) which was also used in Worland (2014) and coincides approximately with the highest salinity values in the field measures. According to Bot (2010) 6.3 g/l corresponds with an approximate electrical conductivity (EC) of 17000 microS/cm. As an initial concentration of the aquifer is either 6.3 g/l taken for saline water, 3.15 g/l (approx. 8500 microS/cm) for brackish or 0 g/l for fresh water.

Table 1: overview of the model parameters

Parameter	Symbol	Unit	value
Length x (columns)	x	meter	3500 (175 cells)
Depth y (layers)	y	meter	110 (55 layers)
Wide z (row)	z	meter	200 (1 cell)
Conductivity Clay	K_c	m/year	0.365
Conductivity Sand	K_s	m/year	4106.25
Effective porosity Clay	n_{ec}	-	0.4
Effective porosity Sand	n_{es}	-	0.25
Stress period length	t_{stress}	year	1, 10, 100, 250, 500, 500
Number of time steps per stress period	t_{steps}	year	10
Recharge	R	m/year	0.025
DRHODC	$\Delta\rho/\Delta C$	-	0.7
Vertical anisotropy	-	-	1:10

2.2.5. SCENARIOS TO TEST THE HYPOTHESES

Several scenarios have been applied in the model to see what factors may explain the formation and the shape of the fresh water lens beneath the elevated area. First, the processes that cause the formation of fresh water lens by different qualities of recharge and initial concentration of the aquifer have been looked at. A division in five conceptual scenarios have been made that differ in initial value of the chloride concentration and the quality of the recharge. The initial concentration value have been used to see if it the lens is caused by freshening or salinization of the aquifer. So, the difference in recharge, either all fresh or saline (homogenous recharge) and a difference in the quality of the recharge (heterogeneous) have been looked at. The initial concentration value has been changed to see if the formation of the fresh water lens is caused by freshening of salinization of the aquifer. The recharge is either completely fresh of saline (homogenous) or a combination of both (heterogeneous). This is done to see if the formation of the lens is caused by differences in the salinity concentration of the recharge.

Table 2: Overview conceptual scenarios.

Scenario	Initial concentration	Recharge
C1	Fresh (0 g/l)	Homogenous Saline (6.3 g/l)
C2	Saline (6.3 g/l)	Homogenous Fresh (0 g/l)
C3	Saline (6.3 g/l)	Heterogeneous
C4	Fresh (0 g/l)	Heterogeneous
C5	Brackish (3.15 g/l)	Heterogeneous

After the modeling of the conceptual scenarios, the scenario with the best resemblance of the saline distribution found during the fieldwork have been used to further investigate other factors that could influence the freshwater lens. Other factors that have been investigated with scenarios were: ponds, elevation, groundwater flow direction and thinner spots in the clay layer. These scenarios have been compared to see their influence on shape, head, flow lines, concentration gradient and recharge.

The scenarios investigate the role of recharge in the formation of the freshwater lens and therefore it tests hypotheses 1, 2 and 3. The scenarios with a change in elevation (E1 and E2) have been simulated to test hypothesis 1. The scenarios with ponds (P1, P2 and P3) have been simulated to test hypothesis 2. The scenario with a change in lithology (TC1) has been simulated to test hypothesis 3. The scenarios are further elaborated in the results.

Table 3: Quick overview of the scenarios

Scenario	**Description**
P1	Ponds distributed over the elevated area
P2	Ponds distributed according to the field measurements
P3	Ponds according to field measurements and shrimp farms
E1	Elevation is multiplied five times
E2	No elevation
R1	Groundwater flow both directions
R2	Groundwater flow in southern (right) direction
TC1	Multiple spots with thinner clay

3. RESULTS

This chapter is divided into two parts and describes the results of the fieldwork and the modeling. The fieldwork has been done in the coastal area of Bangladesh between 03-01-2017 and 16-02-2017. The results of the fieldwork consist of the results of the lithology, electrical conductivity of the water samples and the geophysics results. At the end of the fieldwork part an answer is given to research sub-questions 1 and 2. The second part of this chapter describes the results of the modeling and gives an answer to the third research sub-question. In this chapter an electrical conductivity value of 0-2000 microS/cm is used as fresh, 2000-4000 microS/cm as brackish and 4000-30000 microS/cm as saline.

3.1. FIELDWORK

3.1.1. LITHOLOGY

At the 14 locations boreholes of around 46m (150 ft) deep have been made and documented during the construction of the piezometers (figure 3.1). 13 location are within the study area and 1 location (piezometer 9) is located outside the study area. At all 13 locations there is a confining clay layer at the surface that varies between 3m (10ft) and 12m (40ft). The clay layer at Piezometer 9 is much more thick, around 35 m. In general there is a sandy aquifer beneath the confining clay layer, therefore roughly it is a two layered system of a sandy aquifer with a confining clayey aquitard.

However as can be seen in figure 3.2, the reality is slightly more complex. The clay layer consists of clay with layers and pockets of silty clay, clay loam and silty clay loam. The sandy aquifer consists of sand with grain sizes between medium (210-300 micro m) to fine (150-210 micro m) and very fine (90-15 micro m) with some deeper embedded clay layers. At the background of figure 3.2 a simplified interpretation of the soil is visualized, where the subsurface is divided into a confining clay layer and a sandy aquifer with pockets of clay.

Traces of organic material like dead plant material, pieces of wood, shells and humus have been found at several locations, mostly in the clay. A layer of pebbles is found in the clay under the ‘old creek’ which indicates that it used to be a river.

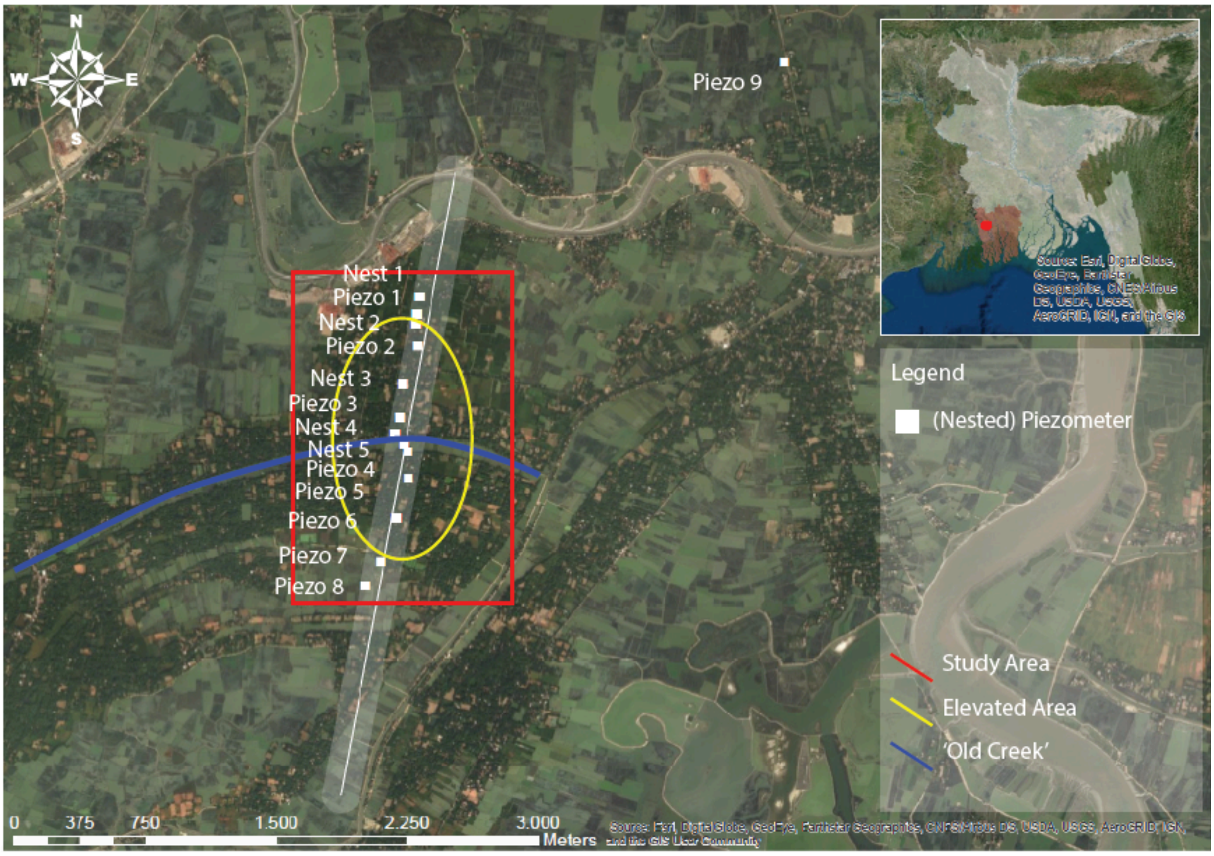


Figure 3.1: map of the locations of the (nested) piezometers in Assasuni.

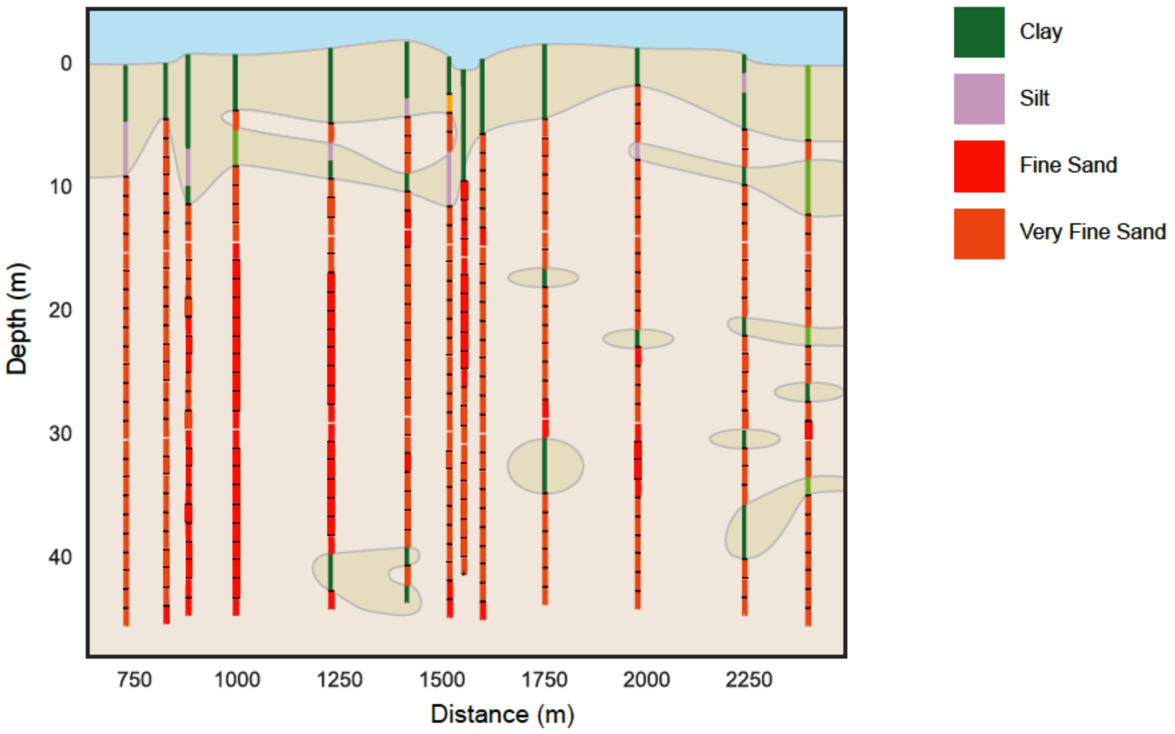


Figure 3.2: Cross-section of the lithology at the piezometers in Assasuni.

3.1.2. ELECTRICAL CONDUCTIVITY (EC)

Aquifer: See figure 3.3 for the location of the tube well (circles) measurements. The EC of the tube wells varies from 621 microS/cm to 8420 microS/cm and the fresher groundwater is found on the elevated area. The brackish and saline groundwater tube wells are found at the edges and the area surrounding the elevated area, especially the tube wells in the South are more saline.

The cross-section is visualized as the white line across the elevated area from North to South. The measurements inside the 100m buffer around the cross-section are visualized in figure 3.4. In the cross-section it is also visible that the tube wells at the edges of the elevated area are more saline. Most of the tube wells are between 10m and 20m deep. There is only one substantially deeper tube well which is also more saline.

The EC of the water samples from the piezometers (squares) also show that the water at the edges and next to the elevated area is more saline while the water is fresher beneath the elevated area. Besides, the measurements show that the deeper groundwater is less fresh than the shallower groundwater. What stands out is that the shallow (around 8m) groundwater along the ‘old creek’ is very saline (around 6500microS/cm), but the more middle deep (around 24m) is much fresher (1000-1600 microS/cm). This could indicate that there was saline water recharge along the ‘old creek’.

Groundwater in confining clay layer: The electrical conductivity of 7 hand auger boreholes has been determined and range from 816 to 13110 microS/cm, (figure 3.3, diamonds). The depth of the boreholes range from 2.0 to 5.2m in which only clay is found which is very dense and heavy.

At one borehole (figure 3.4, diamonds) two water samples have been taken at different depths, at 3.0m (816microS/cm) and 5.2m (827mircroS/cm). The vertical change in EC is negligible in the clay at this borehole. The boreholes at the edge of the elevated and near the ‘old creek’ in the middle are more saline, which matches the other observations. Thus the groundwater in the clay has the same spatial distribution of EC as the surface water and the groundwater in the aquifer.

Surface water (Ponds): The electrical conductivity of 33 ponds has been measured and varies from 330 to 13470 microS/cm, (figure 3.3, triangle). Most of the ponds are fresh except for the edges of the elevated area and in the ‘old creek’ in the middle (where a strip of fields separates the northern and southern part). Especially at the southern edge several ponds that are used for shrimp farming, are very saline ranging from 9892-13470 microS/cm.

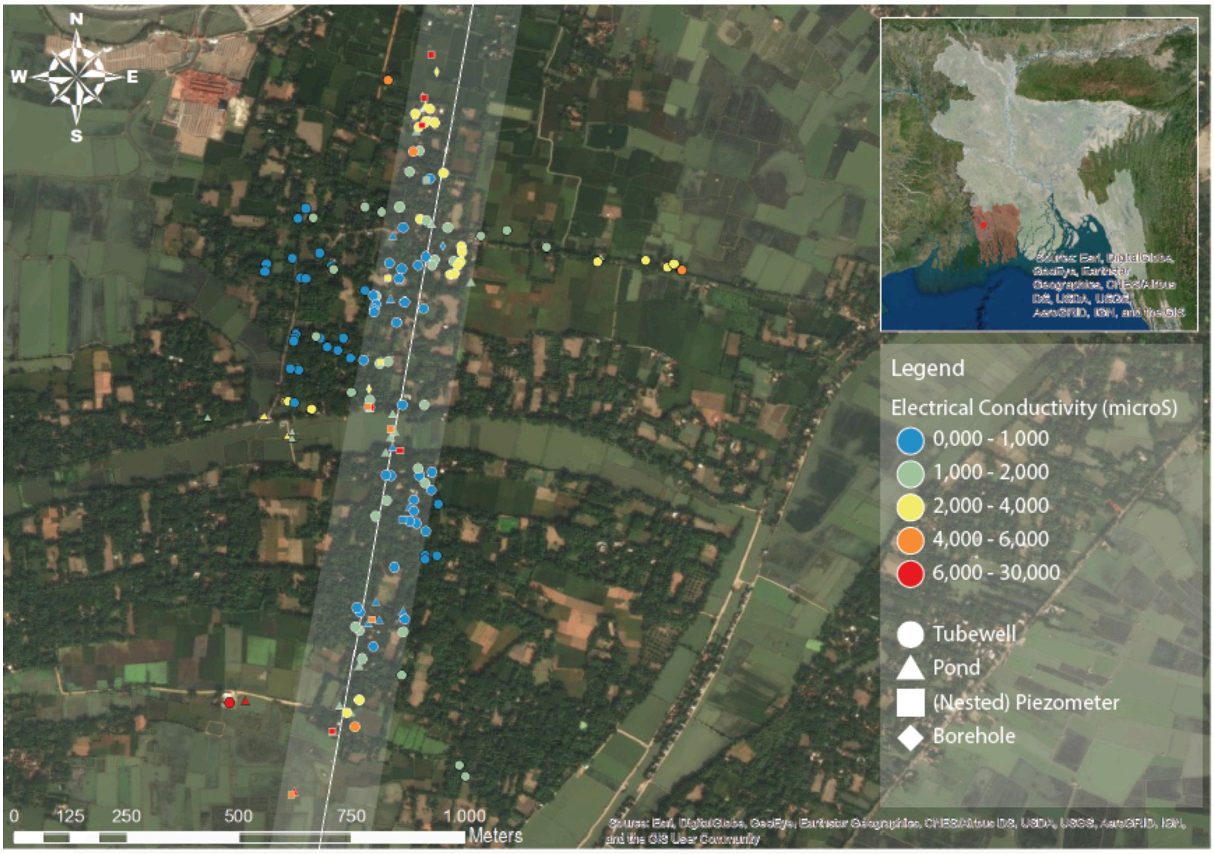


Figure 3.3: map of the electrical conductivity measurements in Assasuni, in the appendix are the water samples split up for each type.

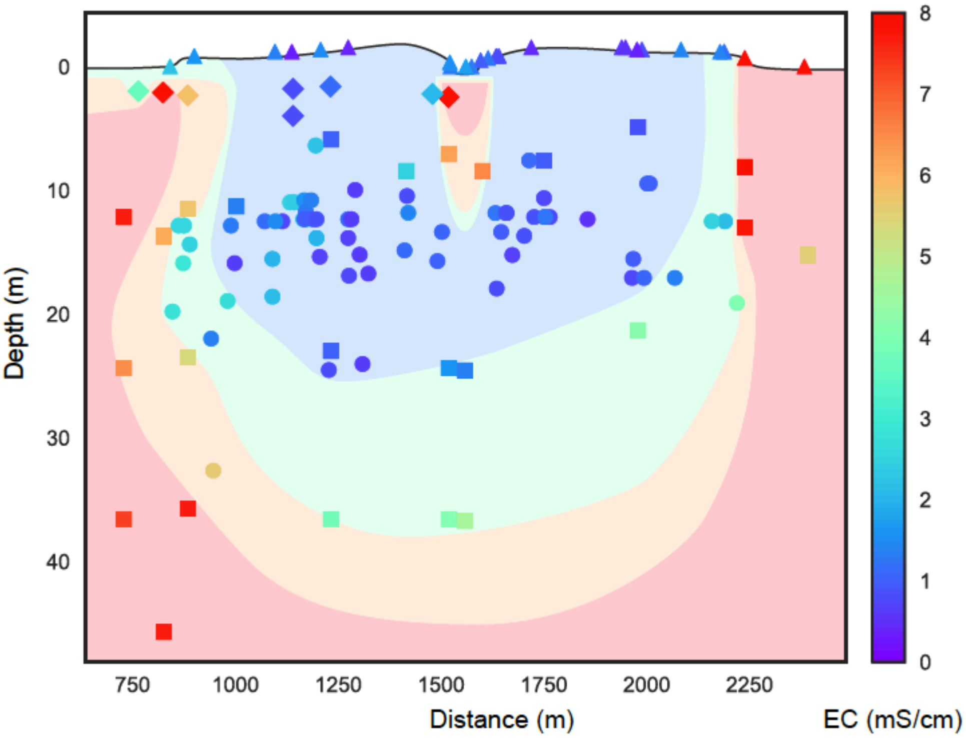


Figure 3.4: Cross-section of the electrical conductivity measurements in Assasuni.

3.1.3. GEOPHYSICS

Vertical electrical sounding (VES): In total there have been 3 vertical electrical soundings (VES) experiments conducted and 5 soundings profiles. See figure 3.5 for the locations of the experiments. Both resistivity curves of AS1 and AS2 are given in figure 3.6. The plus signs are the measured resistivities and the smooth line is the modeled curve with the input layers (blocked line). The x-axis is the half-length distance of the outer electrodes, thus the length from the outer electrodes to the middle. The length (L) between the outer electrodes is related to the depth by depth = L/6.

The resistivity curves of AS1 and AS2 show roughly the same shape of the curve. At first the resistivity declines, this can be explained by the unsaturated top soil. The unsaturated clay has a higher resistivity because air makes the soil more resistive. Then at around half-length 6m for AS2 and 11m for AS1 the resistivity goes up. This is due to a layer with a higher resistivity which can be interpreted as the sandy aquifer, because sand has a higher resistivity than clay. At the end the resistivity curves go down which is caused by a lower resistivity due either clay or more saline water.

The shape of the resistivity curves is similar but the values are not. The resistivity curve of AS1 varies between 5 and 6 Rho or Ohm-meter. This is significantly lower than the resistivity of AS2 which varies between 19 and 25 Rho. The lithology gives around the same image thus this difference is due a difference in salinity. Therefore it can be concluded that the groundwater in the middle of the elevated area is significantly fresher than the groundwater in de area surrounding the elevated area. The biggest difference between resistivity of AS1 and AS2 has been found at a half-length of around 22.5m0. Therefore, a depth of 7.5m (L/2 = 22.5m → 22.5/3 = 7.5m) was chosen to do the profiling.

Figure 3.5. Locations of the geophysics measurements.

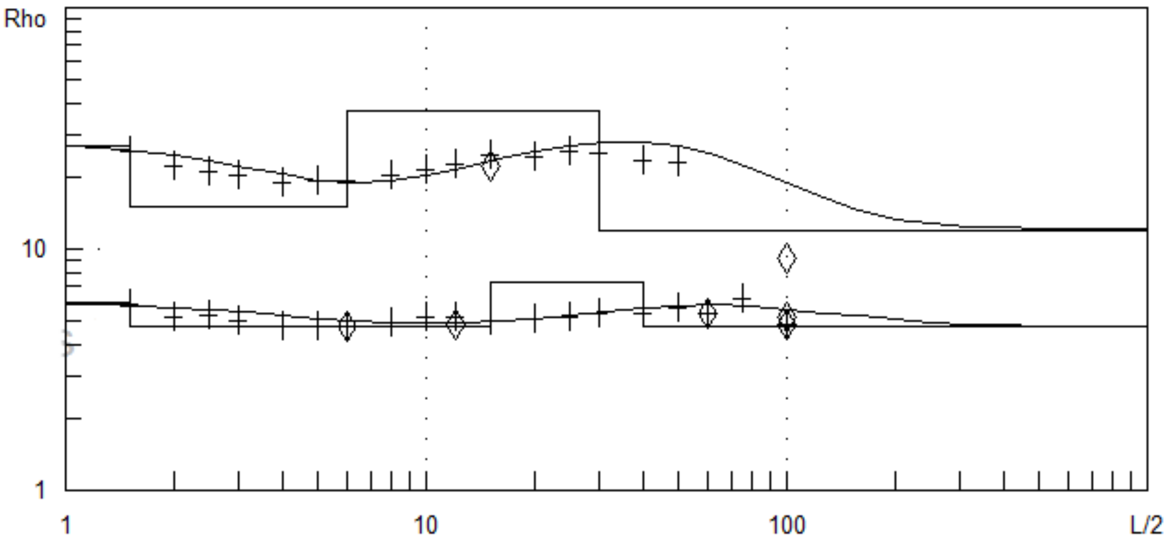


Figure 3.6: Resistivity curves of AS1 (lower curve) and AS2 (upper curve). The x-axis shows the half-length(m). The y-axis shows the resistivity (Rho). Note that both axes are in logarithmic scale.

Profiling: The profiling has been done at a depth of 7.5m, which results in a spacing distance of 15m in the Wenner Array (d=L/6 → L=45 → 45/3 = 15m). The profilings AP1, AP2, AP4 and AP5 are on the crossection from North to South and AP3 is situated from East to West from outside the elevated area to the middle of the elevated area (figure 3.5). The resistivity of the profilings is shown in figure 3.7, where a gradient is visible in profilings AP2 and AP5 from the sides to the middle of the elevated area. Thus the salinity decreases towards the middle of the elevated area. The resistivity increases at AP5 away from the old river in the middle, which suggests that the groundwater is more saline around the old river in the middle of the elevated area.

Figure 3.7 shows the resistivity of AP3 which goes from the lower lying area to the elevated area in the East to the middle of the elevated area. Where there is the same gradient in resistivity visible. The resistivity is higher on top of the elevated area than at the surrounding area, which suggests that there is also a salinity gradient in East-West direction at that location. The clay layer is thinner at piezometer 6, which explain the higher peak in resistivity in AP4 than AP2. These curves show that the gradient in salinity gradually rises towards the middle of the elevated area.

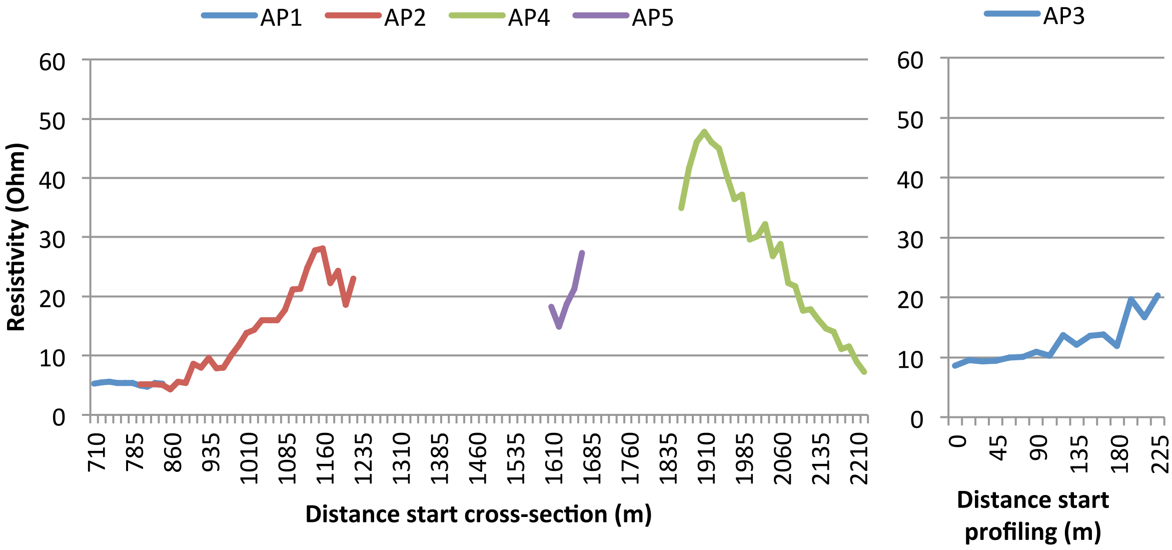


Figure 3.7: Profiling of AP1,2,4,5 from North to South and AP3 from East to West.

3.1.4. GROUNDWATER TABLE

The groundwater tables in the piezometers have been measured relative to the surface, by measuring the depth of the water table relative to the top of the piezometer and subtracting the height of the top of the piezometer to the surface (figure 3.8). Subsequently the relative height of the ground has been measured by a technical team using a digital leveler and a levelling staff. The relative height of the surface is also used in the visualization of the cross-sections. The water table decreases from South to North by around 1.5m over a distance of 1.5km, which suggests a groundwater flow in northern direction.

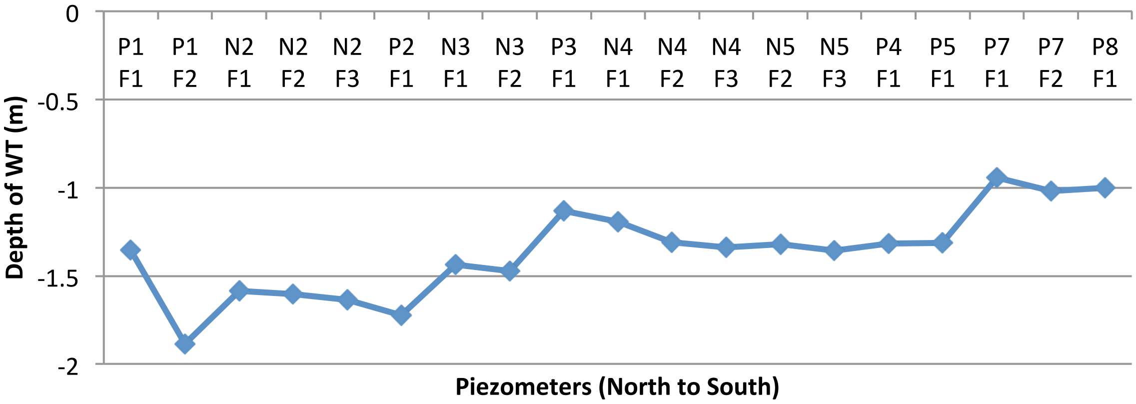


Figure 3.8: Depth of the Water tables below groundlevel in the piezometers at 12-02-2017.

3.1.5. CONCLUSION OF THE FIELDWORK

The results of the fieldwork (figure 3.9) are used to answer the first and second sub-questions of this study: *1. What is the local variability of salinity of the groundwater on and around the elevated area in Assauni?*

The electrical conductivity results of the surface water (ponds), the confining clay layer and the aquifer show the same spatial distribution of salinity. The water at the elevated area is fresher while the surrounding area and the edges of the elevated area show more brackish and saline water, besides the water at the 'old creek' is more saline.

The EC measurements match the observed resistivity during the geophysics experiments. The measured resistivity indicates the same pattern of fresh water beneath the elevated area and increasingly more saline toward the surrounding area in both North-Souths as East-West direction. This coincides with the measurements of the previous fieldwork done by Floris Naus.

The ponds are rainwater fed and seem fresher than the groundwater underneath, which could indicate of freshening of the aquifer due to ponds. Besides the deeper groundwater in general is more saline than the shallower, except at the 'old creek' in the middle where the shallow groundwater is saline. However, the deep groundwater is more saline than the middle deep groundwater. This results in the pattern at the 'old creek' from the surface of brackish, saline, fresh and finally brackish.

Thus, these salinity measurements indicate a freshwater lens beneath the elevated area in Assasuni with a small saline lens beneath the 'old creek' (figure 3.10).

2. What is the local lithology of the subsurface on and around the elevated area in Assasuni?

The lithology varies slightly across the study area but there is no clear distinction between the elevated and the lower lying surrounding areas. In general there is a two layered system consisting of a sandy aquifer beneath a confining clay layer. The clay layer varies little in the study area but further away from the study area at Piezometer 9 it is much thicker.

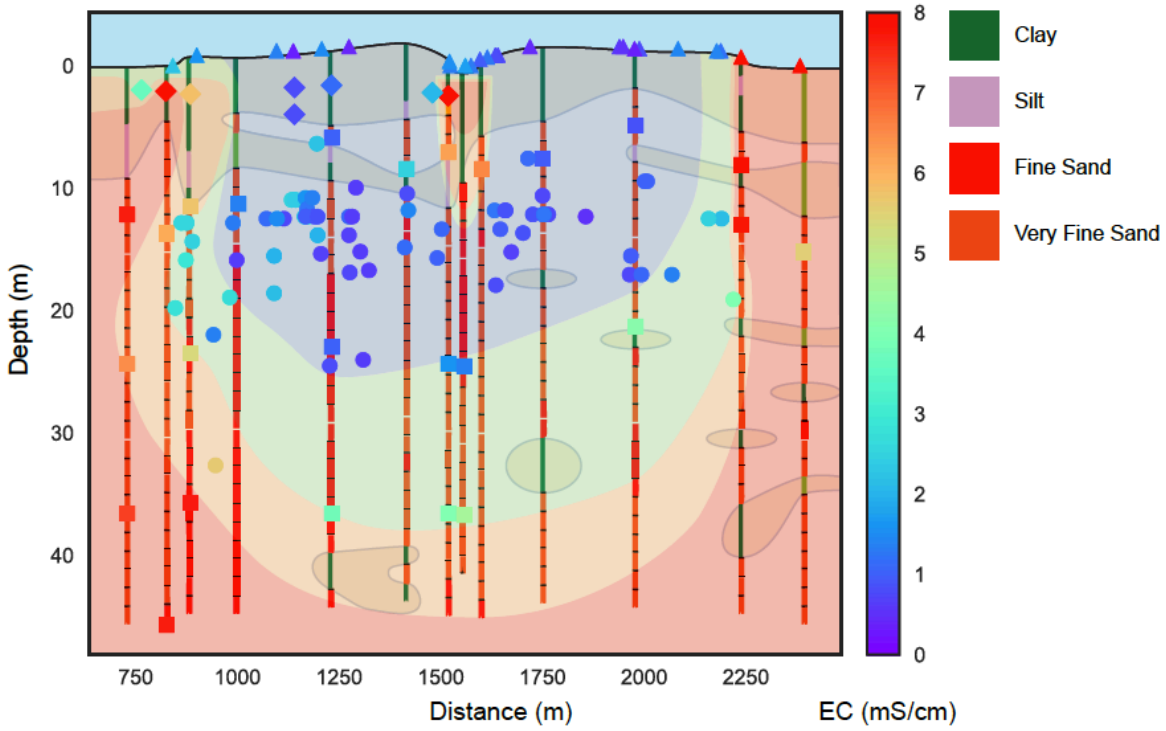


Figure 3.9: Cross-section of the electrical conductivity and lithology in Assasuni.

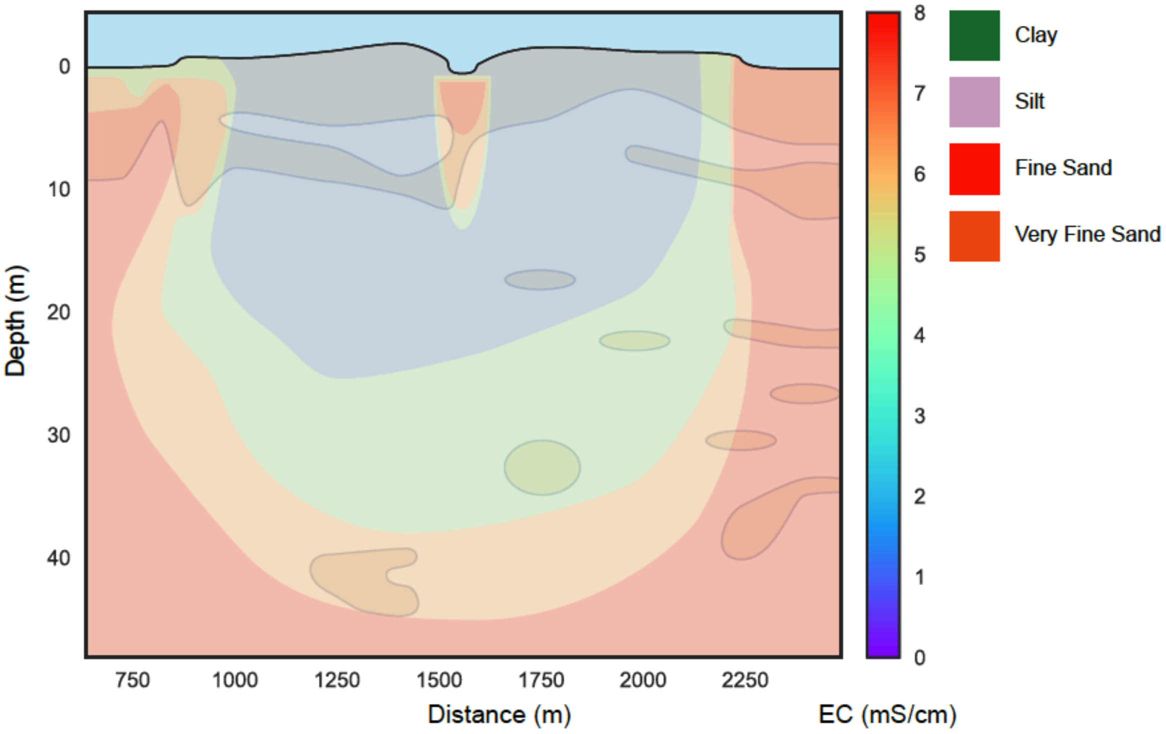


Figure 3.10: Interpretation of the salinity and lithology in Assasuni.

3.2. MODEL RESULTS

3.2.1. CONCEPTUAL SCENARIOS

The five scenarios with differences in initial concentration and recharge quality show that after approximately 100 years the recharge goes as piston flow through the confining clay layer on top (figure 3.11). At some places this happens earlier, where the clay layer is thinner. The first two scenarios (C1 and C2) show the situation of salination and freshening due to homogenous recharge. First the clay layer gets saline (C1) or fresh (C2) then the recharge reaches the aquifer after approximate 100 years and then is a clear difference visible. Due to density difference causes the buoyancy effect that the fresh water stays on top of saline water. In the salination scenario C1 is visible that the recharge of saline water causes salt fingers, like discussed in Simmons et al. (1999). In the salination scenario is no vertical concentration gradient visible within the aquifer, but the whole aquifer gets equally more saline during the simulation run. In the freshening scenario C2 a steep vertical concentration gradient is visible because the fresh water stays on top of the saline water. In both scenarios C1 and C2 with homogenous recharge, there is no difference visible between the elevated area and the lower lying areas. Thus the freshwater lens in caused by a difference of salinity in the recharge.

The scenarios C3, C4 and C5 have a mix of saline and fresh recharge. The recharge on top of the elevated area is fresh because it assumes that the elevated area gets less flooded with saline water and the ponds were fresh during the field research. It is assumed that in the lower lying area the recharge is saline because it gets inundated with saline water during floods and that the water in ponds were more saline during the field work and there are saline shrimp farms.

All the scenarios C3, C4 and C5 have the same recharge but the initial aquifer quality differs per scenarios between saline (C3), fresh (C4) and brackish (C5). In all these three scenarios is the forming of a freshwater lens visible. The same density difference buoyancy effect is visible as in the C1 and C2 scenarios. The freshwater stays on top in the C3 scenario and salt fingers occur in the C4 scenario. The concentration gradient is bigger in the C3 than the C4 scenario in the vertical direction. But in the horizontal direction is the gradient bigger in the C4 scenario. In the C3 scenario the freshwater forms a lens beneath the clay layer but not only beneath the elevated area also beneath the lower lying area, this is due to more density driven flow. The difference between the elevated area and the lower area is better visible in the C4 scenario. The C5 scenario with a brackish initial condition lies in between these two scenarios and the results correspond the best with the measurement data during the fieldwork. Therefore the C5 scenario with heterogeneous recharge and initial brackish conditions will be used as the standard scenario for the rest of the analyses.

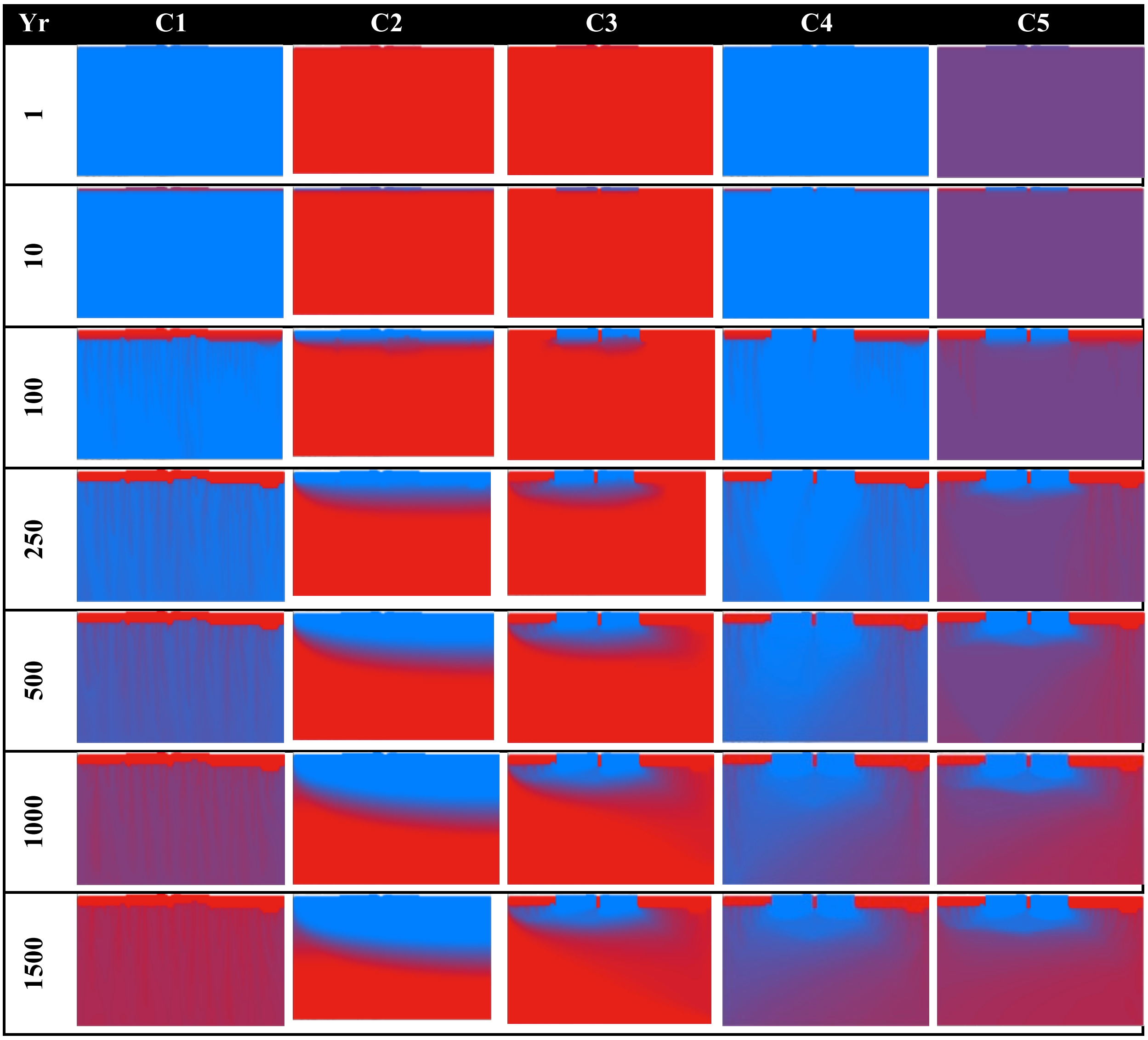


Figure 3.11 : Results of the five conceptual scenarios.

3.2.2. OTHER SCENARIOS

Ponds: In the scenarios P1, P2 and P3 modeled ponds are added to the standard scenario C5. At the P1 scenario there are 11 fresh (0 g/l) ponds added randomly across the elevated area. The modeled ponds have a constant head value of 0m. The head around these ponds increase and cause for an increased recharge of freshwater on the elevated areas. The total recharge of the P1 scenario is 420m3/year and is 21.4% more than in the standard scenario C5 with 345m3/year. This increase in freshwater recharge is visible in a bigger freshwater lens. The fresh/salt interface is approximately 6 meter deeper than in the standard scenario. The P2 scenario has a total of 17 ponds from which 14 are fresh and 3 saline. The fresh ponds are in the same locations on the elevated area as the field measurement and the 3 saline ponds are in the middle where the old river is situated. There are more ponds which results also in more recharge. The P2 scenarios has 28.6% more recharge than the standard. The shape of the freshwater lens is the same only slightly bigger. In the P3 scenario there are also saline shrimp farms added at the southern part (right). This results in a lot more saline recharge at the southern and lower areas which makes the aquifer more saline in general and a smaller freshwater lens forms beneath the elevated area. The total recharge of P3 is 65% bigger in comparison to the standard C5 scenario.

Elevation: The scenarios E1 and E2 investigate the influence of elevation in the formation of the freshwater lens. Scenario E1 multiplies the elevation of the elevated area five times while E2 has no difference in elevation. There is no influence in the shape and the amount of recharge due to differences in elevation in the model. Thus, elevation doesn't affect the formation of the freshwater lens directly.

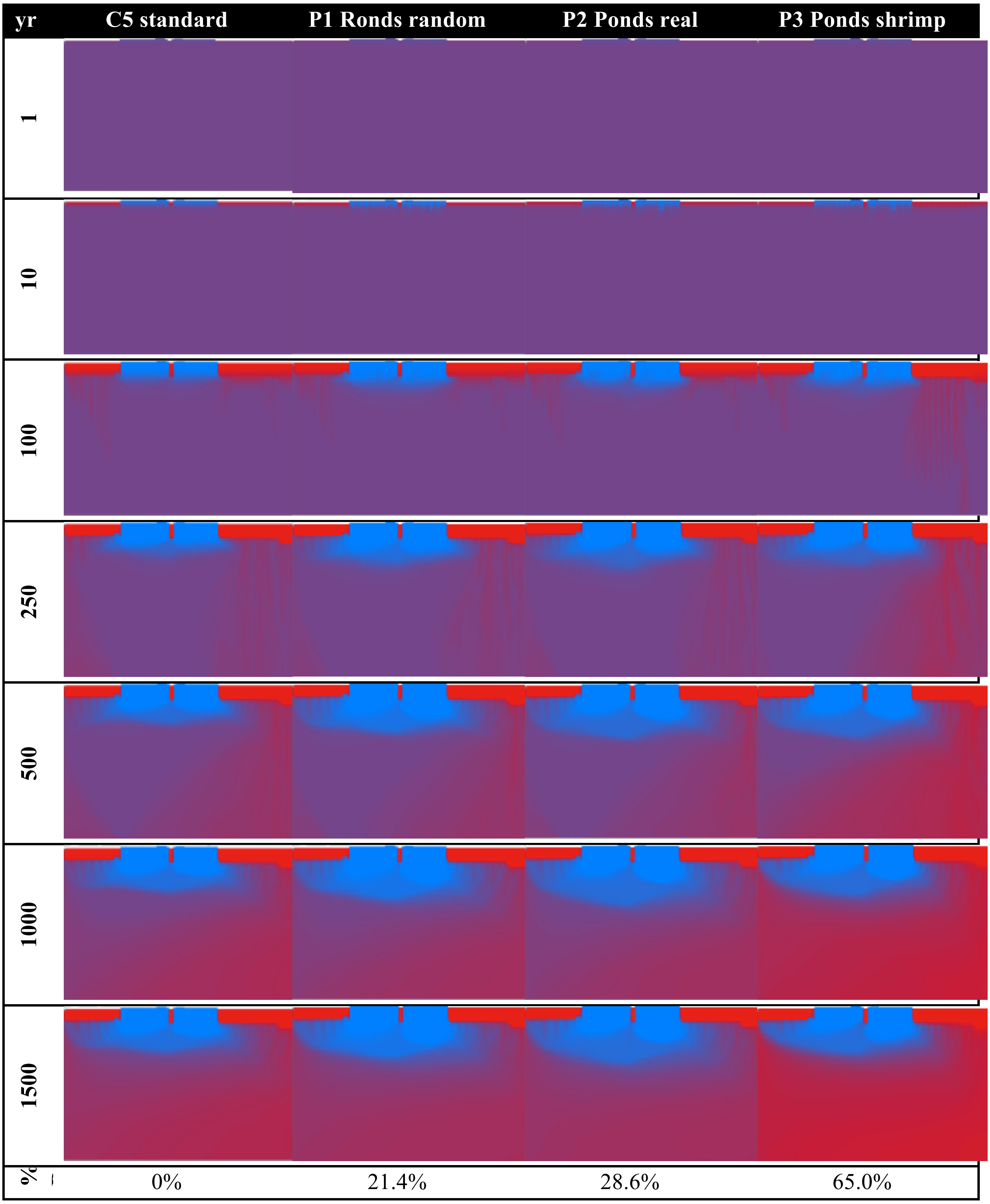


Figure 3.12: Results of the pond scenarios.

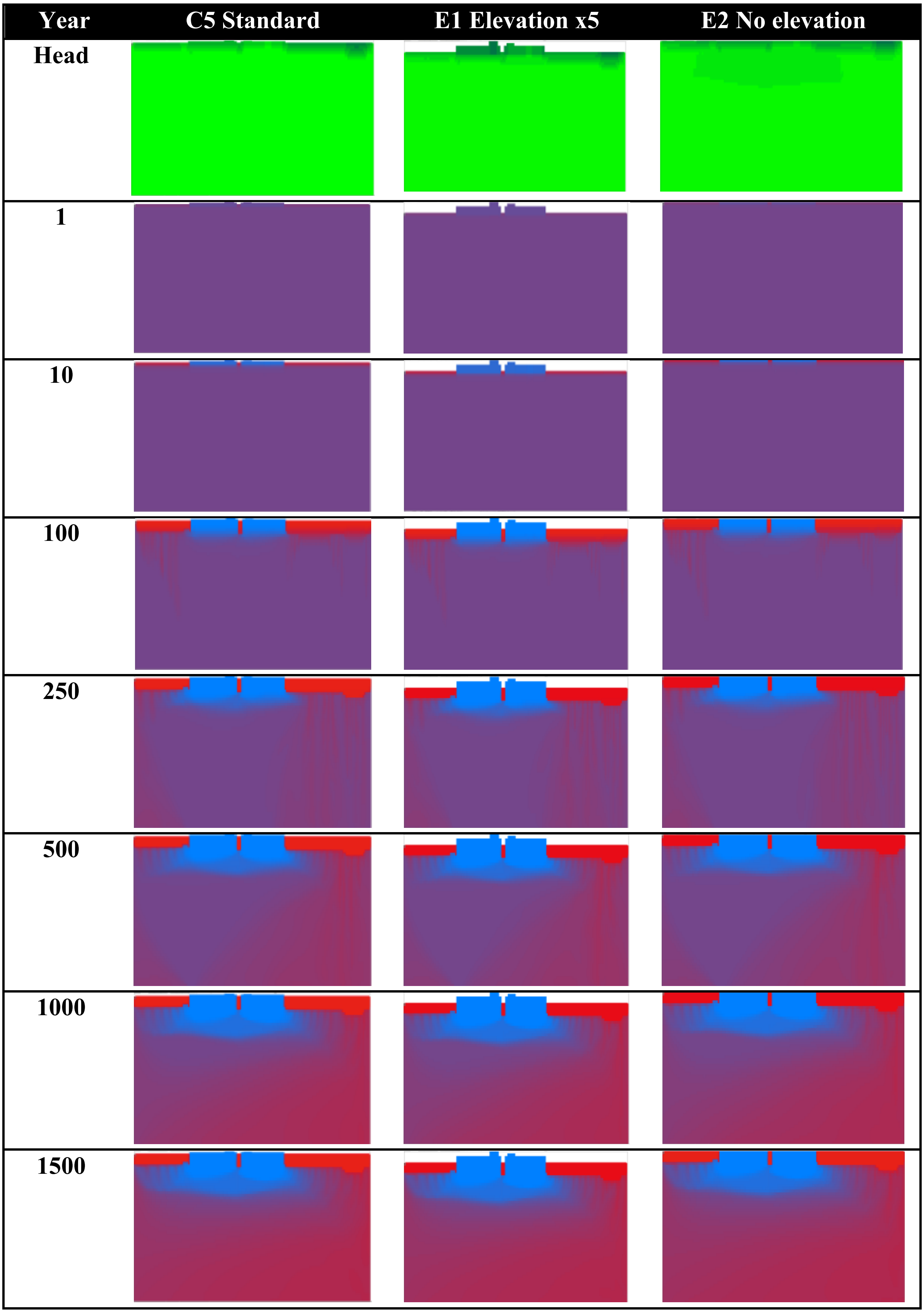


Figure 3.13: Results of the elevation scenarios.

River flow direction: The groundwater in the aquifer flows in the standard model to the north (left), as measured during the fieldwork. The R1 and R2 scenarios test the influence of groundwater flow direction on the shape of the freshwater lens. The flow is altered by the connection of the rivers to the aquifer. In the standard scenario, only the northern river is connected to the aquifer and the groundwater flows towards the northern river. In the R1 scenario both rivers are connected to the aquifer. In the R2 scenario only the southern river is connected. The model shows that the flow direction of the groundwater alters the shape of the freshwater lens. The standard scenario has a flow to the north and shifts the water lens a little to the north. The groundwater flows in both directions, (R1) flows almost symmetrical to both boundaries of the model. The shape of the R1 scenario is also more symmetrical. The R2 scenario shows the opposite of the standard scenario in terms of groundwater flow and the shape of the freshwater lens is therefore more shifted to the south. In all these scenarios the depth of the salt-fresh interface is equal. So the connection of the river has a big influence on the groundwaterflow and the groundwater in turn, has again a big influence on the the shape of the freshwater lens.

Thinner clay spots

In the standard scenario there is a thinner spot in the confining clay at the location of Piezometer 6 (thin spot most right side). Scenario TC1 is a scenario where more spots are added with a thinner clay layer, in total are there 5 spots where the clay is approximately 3 meters thick (figure 3.14). The thickness of the clay layer is different in scenario TC1, which changes the water flow locally, but there are no clear changes visible in neither the shape of the freshwater lens nor in the depth of the salt-fresh interface.

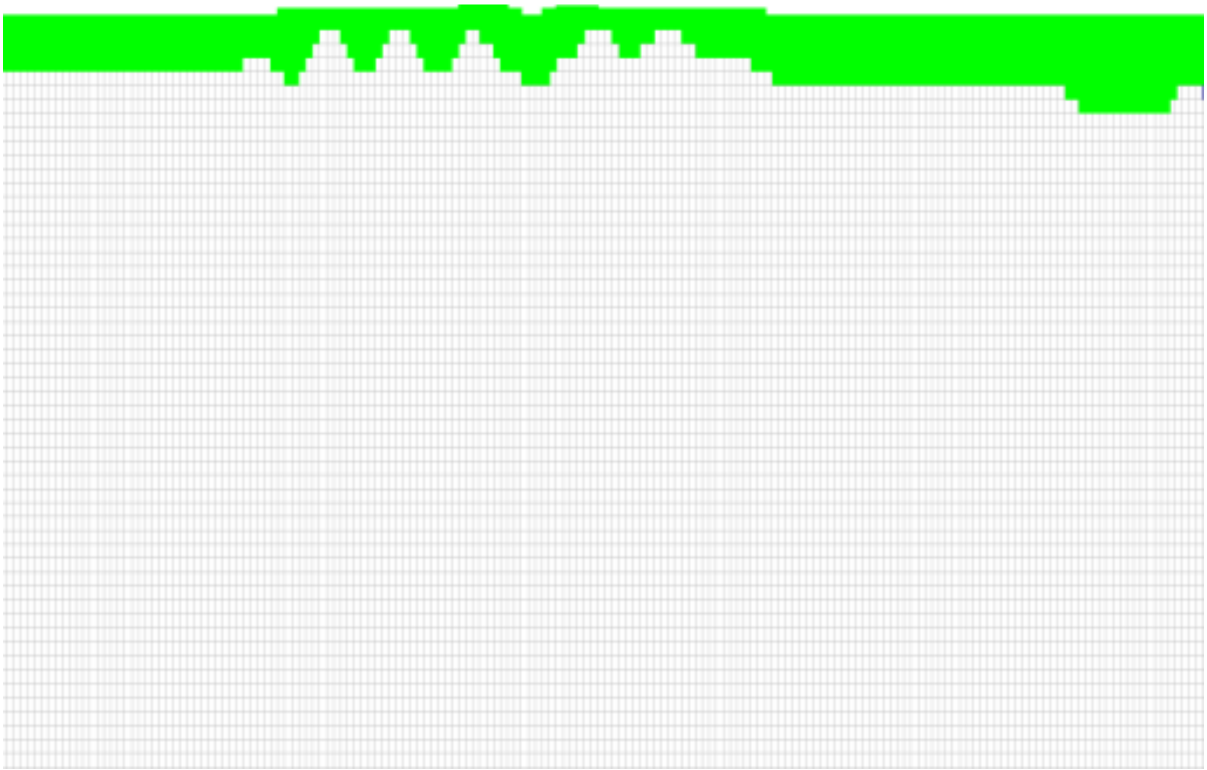


Figure 3.14: The clay layer of scenario TC1 with 5 spots where the clay is more thin.

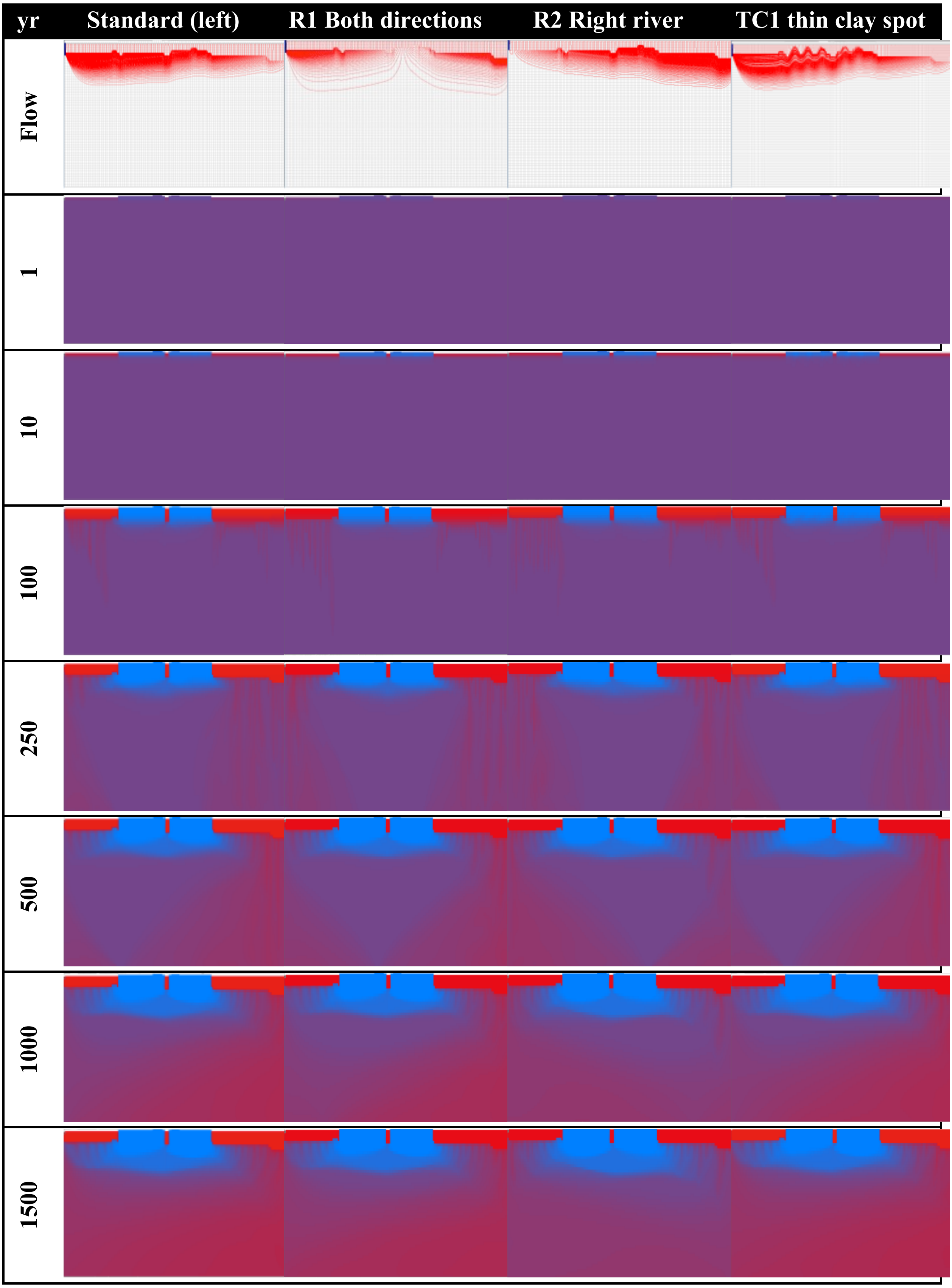


Figure 3.15: Results of the flow direction scenarios and of the thin clay layer scenario.

3.2.3. CONCLUSION OF THE MODELING

The results of the modeling are used to answer the third sub-questions of this study: *What factors may explain the freshwater lens in the shallow aquifer beneath the elevated area in Assasuni?* According to the model, the freshwater lens beneath the elevated area is best explained by differences in recharge with different initial salinity. No formation of a freshwater lens was visible in the scenarios with homogenous recharge, but it occurs with heterogeneous recharge. So the fresh groundwater lens is at the location where there is fresh recharge. However it cannot be determined if the freshwater lens is caused by freshening or salinization of the aquifer, because in either fresh (0 g/l) or saline (6.3 g/l) initial conditions is the formation of a freshwater lens possible over time.

Freshwater ponds increase the recharge of freshwater beneath the elevated area. This causes the freshwater lens to grow bigger and deeper. However, there is also more saline recharge due to shrimp farms, which diminishes the effect of the freshwater ponds. The scenarios with elevation differences don't show differences in the formation of the freshwater lens, therefore the model suggests that elevation on its own doesn't have influence on the formation of a freshwater lens. According to the field measurements, the groundwater flow is expected to be in northern direction, because the head in the piezometers decreases in northern direction. The model shows that groundwater flow has a big influence on the shape of the groundwater lens, because the shape of the groundwater lens is shifted into the direction of the groundwater flow. In addition, thinner spots in the clay don't change the shape of the freshwater lens, only very locally the groundwater flow is altered by the variation in lithology.

4. Discussion

4.1. RELIABILITY OF THE FIELDWORK RESULTS

Geophysics: The resistivity is best measured in an open and dry field like the lower lying area in Assasuni, however in the middle of the village are several factors that could influence the measurements. Therefore it could be that the profiling measurements are a little distorted. Electrical wires and pipelines in the ground could influence the measurements but those aren't expected in the village, because the powerlines are above the ground and water is taken from ponds and tube wells. Besides, ponds could influence the measurements, therefore it has been tried to get a transect with the least as possible ponds close by. The ponds that were nevertheless close by are visible in the data as a drop in the resistivity. Also variation in the subsurface could alter the measurements of the profiling because a thicker or thinner clay layer causes the resistivity to go down or up respectively. Therefore the resistivity is not necessarily directly linked to the salinity during the profiling. However, the resistivity corresponds well with the EC values found in the field, so the change in resistivity is probably due to a difference in salinity and not a change in lithology.

Spatial distribution of salinity and lithology: The accuracy of the EC measurements is assessed. The initially used Eijkelkamp multimeter got less and less accurate over time, especially with higher EC values. Halfway (20 January) through the fieldwork it has been changed to another multimeter made by Hanna which gave more stable results. The water samples of the first part are remeasured by the Hanna multimeter and are thus corrected but the EC could have slightly changed in the bottle over time however these changes are expected to be minimal. The tube wells that weren't sampled were corrected by interpolation of the remeasured values for the EC. Therefore it can be assumed that the EC values are more or less correct.

The GPS of a smartphone is used for determining the location, which could be a couple meters off. This is not a problem because a few meters is within the needed accuracy to determine the pattern of the salinity distribution.

The depth of the tube wells is determined by interviewing the local owners. These didn't know exactly the depth of the tube well but they could make reasonable guesses by remembering how many tubes went into the ground during the construction of the tube well.

The method that was used for the deep drillings and the installation of the piezometers is not very accurate. Because the drill head is constantly going up and down it is hard to determine the exact depth of the sediment sample, the sediments could be coming from a range of around 1.5m. This could mean that some small layers have been missed in the lithology but the thicker layers are noticed.

There are some aspects that could influence the quality of the water sample at the installation of the piezometers. The filters are closed at the bottom by melting and folding the tube, but this doesn't guarantee that it is completely closed. Therefore it could be possible that a little water of around 2m deeper could also enter the piezometer. Probably this is not of big influence because the volume of leaking water is quite small in comparison to the water entering through the filter. Another aspect that could influence the water sample is that after the installation of the piezometer the clay layers are not securely closed off with clay to prevent mixing of different aquifer water.

The organic material is mostly found in the clay layer because the clay stays in chunks together with the drilling method but the sand is loose which could cause that the organic material is flushed away from the sand sediments. Therefore it could be possible that some organic material is systematically missed in the sand sediments. However it is expected that in the sand less organic matter is located, because sand is deposited in flow with higher velocity and therefore less suited for organic material.

The lithology is based on the boreholes of 13 locations in a transect across the elevated area, this results on average in a borehole every 100m to 150m. Which

gives a good impression of the overall subsurface in the area but it could be distorted by change that some details have been missed. It could be that some spots are overlooked where the clay layer is very thin or any other particularities. But in general it can be assumed that the lithology of the 13 locations results in a good image of the subsurface.

Time variations: The depth of the water table was determined on one day, but it could be possible that the heads change between seasons and thus also the direction of the groundwater flow. The placed loggers should confirm or exclude this in time.

Furthermore, it could also be possible that the water quality differs throughout the year and that the salinity is different between the seasons. Though the general differences in salinity are assumed to be constant because the recharge is assumed to be minor through the thick clay layer.

4.2. RELIABILITY OF THE MODEL RESULTS

The reliability of the model is discussed in this paragraph. A model is always a simplified representation of reality. Therefore, the outcomes are subject to inaccuracies with respect to reality. The choice has been made to make a 2D model, while it can be assumed that in reality the flow is not only in North-South direction but also in a 3D manner. In further research it would be good to analyze the effects of a more complex model in 3D, because the elevation and rivers change also in lateral direction.

The assumption is made that the system consists of an aquifer and a confining clay layer, however in reality there are pockets of clay in the aquifer which could alter the groundwater flow. Although these effects are expected to be minor, therefore it is assumed that it doesn't affect the reliability of the results significantly.

For both the recharge and the hydraulic conductivity of clay there are values assumed because no field measurements were done to measure these parameters. Both recharge and hydraulic conductivity of clay are important parameters that have a big influence on the results of the modeling. Therefore more research to these parameters in needed to come up with more reliable results. Because these parameters were assumed, the results are not very exact. Therefore, the values are interpreted indicatively and the exact values of the salinities are not compared by scenario. Also the time of the formation of the freshwater lens is very dependent on the recharge and the conductivity, therefore the exact time that is needed to form this freshwater lens is not accurate. However, the different scenarios can be compared with each other because the used parameters for conductivity and the recharge are kept constant. The different scenarios give an indication on whether the investigated factor has influence or not. The recharge could possible be modeled with another modeling program that is better suited to simulate the runoff and recharge, because recharge is such an important factor in this study.

4.3. INTERPRETATION OF THE RESULTS IN RELATION TO THE HYPOTHESES

Four hypotheses were formulated to explain the variability in salinity: 1) difference in elevation, 2) difference in land use, 3) difference in lithology and 4) difference in depositional environments.

Hypothesis 1: differences in elevation. A difference in elevation has been determined and there is a correlation between the elevation and the freshness of the groundwater. The elevated areas are fresher than the lower lying areas. This suggests that there would be a relation between elevation and salinity. However, according to the model, the elevation on its own has no influence on the formation of a fresh groundwater lens. According to the model is the difference of salinity of the recharge incremental for the formation of a fresh groundwater lens. It is possible that the elevated areas won't get flooded as often as the lower lying area and therefore the recharge on the elevated area is more fresh.

On the other hand, elevation and land use overlap exactly in the study area. The village is located on the elevated area while the lower lying area is used for rice and shrimp cultivation.

Hypothesis 2: differences in land use. The land use and the salinity distribution also coincide. The village is located on the elevated area and fresher groundwater is underneath. Rice paddies and shrimp farms are located in the surrounding lower lying area where there is more saline groundwater. Thus elevation and land use are overlapping completely. The model indicates that the freshwater lens is formed by recharge of different salinity. This difference in recharge can be explained by the land use. The village has fresh recharge due to rainwater and fresh ponds and the surrounding arable land is inundated with brackish water for rice and saline water for shrimp farms. The model shows that fresh ponds could enhance the recharge of fresh water.

Hypothesis 3: differences in thickness of the clay cover. The results from the fieldwork don't show a correlation between the fresher groundwater and the lithology. The field measurements show roughly the same clay layer on top of a sandy aquifer. Thus a local difference in lithology doesn't explain the difference in salinity in the groundwater in the study area. It could be that by change several thinner spots in the clay layer were missed, because at one piezometer (piezometer 6) the clay layer was less thick. But the model suggests that thinner spots in the clay layer change only very locally the groundwater flow and it doesn't influence the formation of the freshwater lens. Therefore it can be concluded that the lithology doesn't explain the spatial distribution of differences in salinity.

Hypothesis 4: differences in depositional environment. The infiltration rate through the clay is expected to be very low (Worland et al., 2015 & Ayers et al., 2016), which can slow down the water system drastically. Because of this also historical differences in depositional environment could explain the current distribution of saline groundwater. At the study area the aquifer starts at around 7m depth, though the aquifer further away at piezometer 9 shows a much thicker clay layer (around 35m). Thus at the study area more sandy material is deposited, which suggests that the study area could be the remnant of a river channel and the area of piezometer 9 a flood plain. The confining clay layer on top of the study area suggest that over time the channel either abandoned its course due to avulsions or received less and less water and evolved into a small tidal creek, which could explain the deposition of clay and silts. This is also visible in the soil map of the FAO (1959) (figure XXX, in introduction). The soil map shows that the soil of the study area is formed by riverine deposits and the soil at piezometer 9 by tidal flat deposits.

This evolution of depositional environments could explain the current distribution of salinity in the groundwater. The old river channel was probably fresh and has deposited sandy material and formed a fresh aquifer. Thus the whole study was expected to be fresh but when the channel weakened and turned into a tidal creek, also more tidal floods started to occur in the region and the lower lying areas were more prone to get inundated which caused the deposition of tidal sediments which caused the saline water to seep into the fresh aquifer that became more saline at the edges and the lower lying area. The same could be true for the old creek in the middle, where the channel evolved into a tidal creek, this tidal creek is more saline which could explain the more saline groundwater beneath the old creek in the middle of the elevated area. This could therefore lead into the salinization of a fresh aquifer deposited by a river channel beneath the whole study area. This is visualized in figure 4.1.

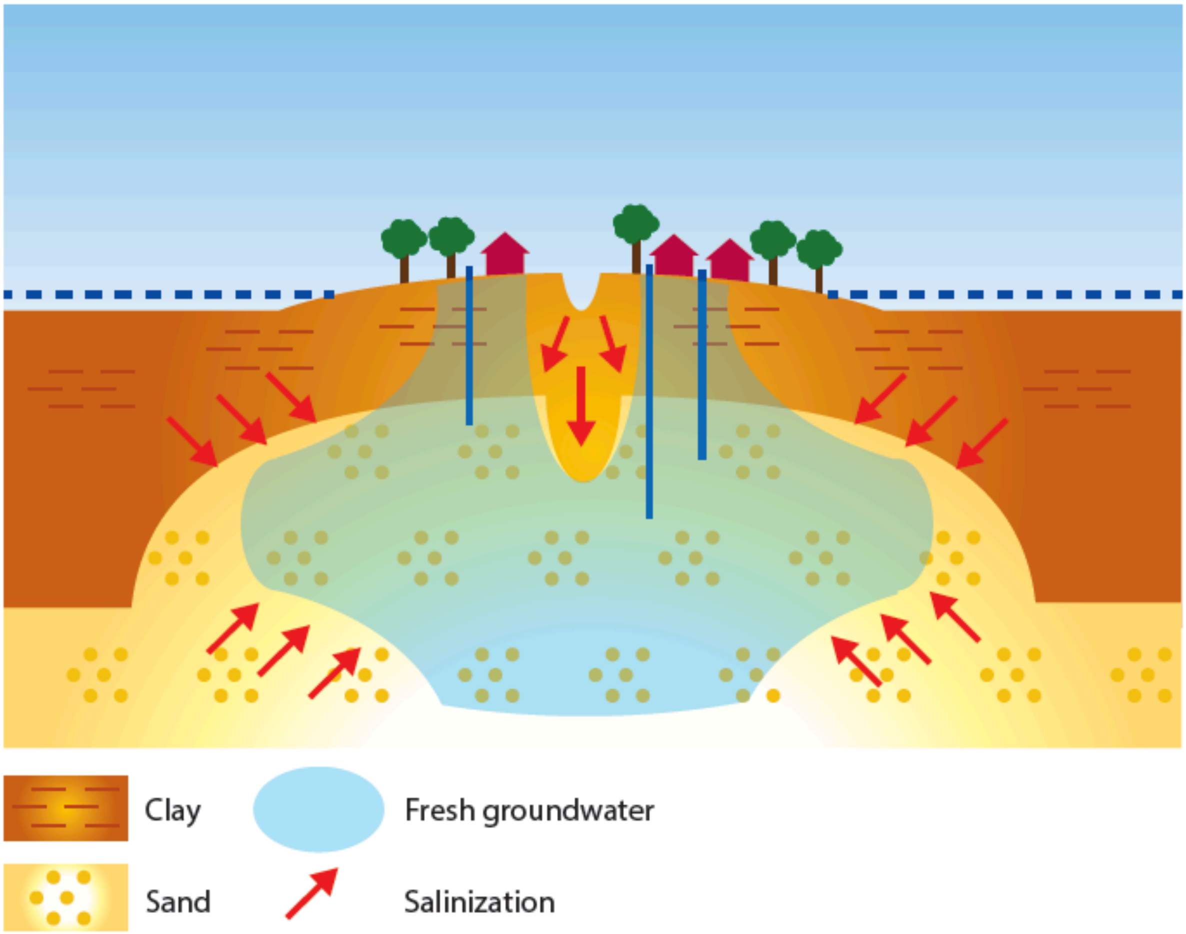


Figure 4.1: conceptual image of the study area which suggest salinization of the groundwater. The area beneath the blue dotted line is more prone to inundation and thus salinization.

4.4. RECOMMENDATION FURTHER RESEARCH

This research contributed to the knowledge on the spatial distribution of salinity in the groundwater of Southwestern coastal Bangladesh by studying the small scale variability of salinity in the groundwater at an elevated area. Already some studies (Ayers et al., 2016; Worland et al., 2015) were done there on the spatial variability of salinity in the region but not yet on this small scale and specific around elevated areas. Also the processes that could explain this variability were investigated by looking at specific factors (elevation, land use, lithology and deposition environment).

However more research is needed to fully understand the processes that cause this variability, because this research has not been able to identify the precise factors. It only provided an indication which factor could play a role and which probably not. Besides more research is needed to tell if these processes also apply in other parts in the region. For instance if these processes apply for other elevated areas or old river channels.

5. Conclusion

The research objective of this study was to map the spatial variability of the salinity of the groundwater in on and around the elevated area of Assasuni and to find the factors that explain this spatial variability. The conclusion is presented by answering the research question: *How can the local variability of salinity on and around the elevated area in Assasuni, Bangladesh, be explained?*

These salinity measurements indicate a freshwater lens beneath the elevated area in Assasuni and more saline groundwater in the lower lying surrounding area, besides there is a small saline lens in the middle of the elevated area beneath the ‘old creek’. The formation of the freshwater lens can be explained by a difference in the salinity of the recharge. Which could be by either less saline flooding because of a difference in elevation or through difference in land use, by fresh ponds in the village on top of the elevated area and by brackish and saline inundation due to rice and shrimp cultivation at the surrounding area.

It is unlikely that the variation in salinity of the groundwater is caused by differences in lithology. Because the lithology varies slightly across the study area but there is no clear distinction between elevated and the lower lying surrounding areas. In general there is a two layered system sandy of an aquifer beneath a confining clay layer.

Another explanation that could explain the current distribution of saline groundwater are historical differences in depositional environment. The aquifer could be fresh because an old river channel was located at the study area which created a fresh aquifer. When the channel weakened and evolved into a tidal creek, finer sediments like clay and silts were deposited in the study area and the area was more influenced by tidal water. The surrounding lower areas were more prone to saline floods and therefore the fresh aquifer beneath the lower lying area became more saline through leeching of the saline water into the aquifer.

This research gives some indications on what processes cause the variability of the groundwater in the southwestern coastal area of Bangladesh, but more research in needed to fully understand these processes.

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Appendix

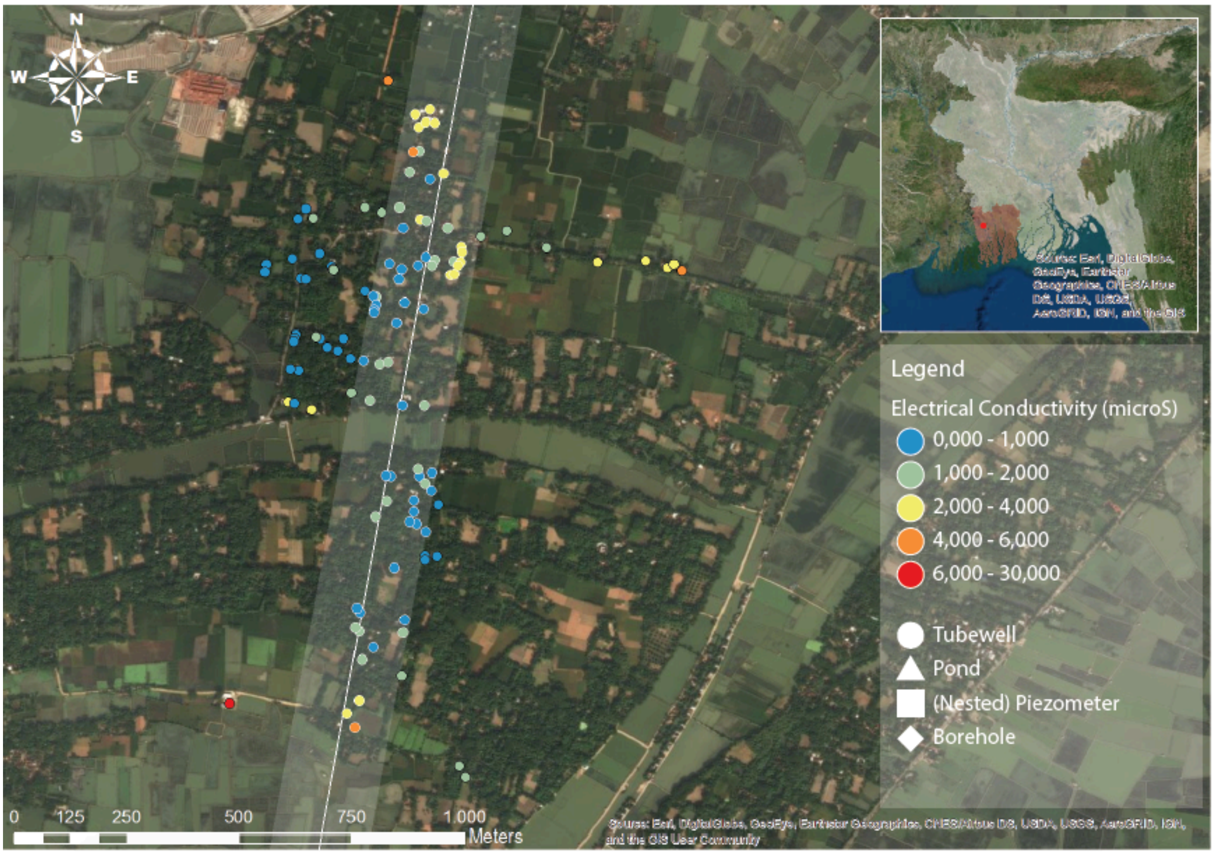

Figure A1: map of the electrical conductivity of tube wells in Assasuni.

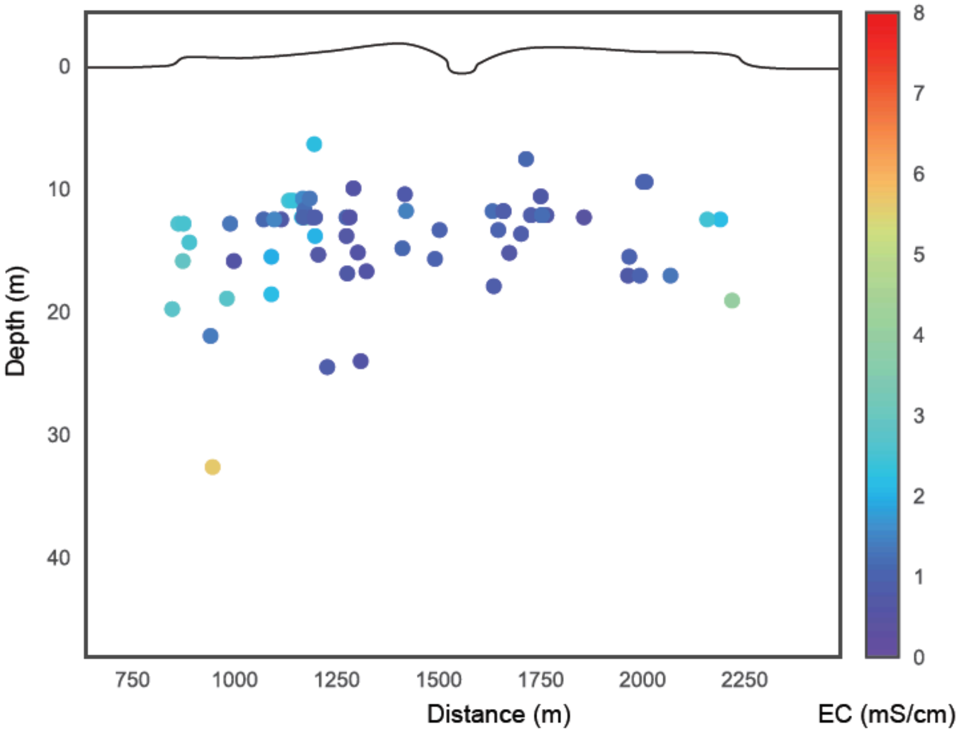

Figure A2: Cross-section of the electrical conductivity of tube wells in Assasuni.

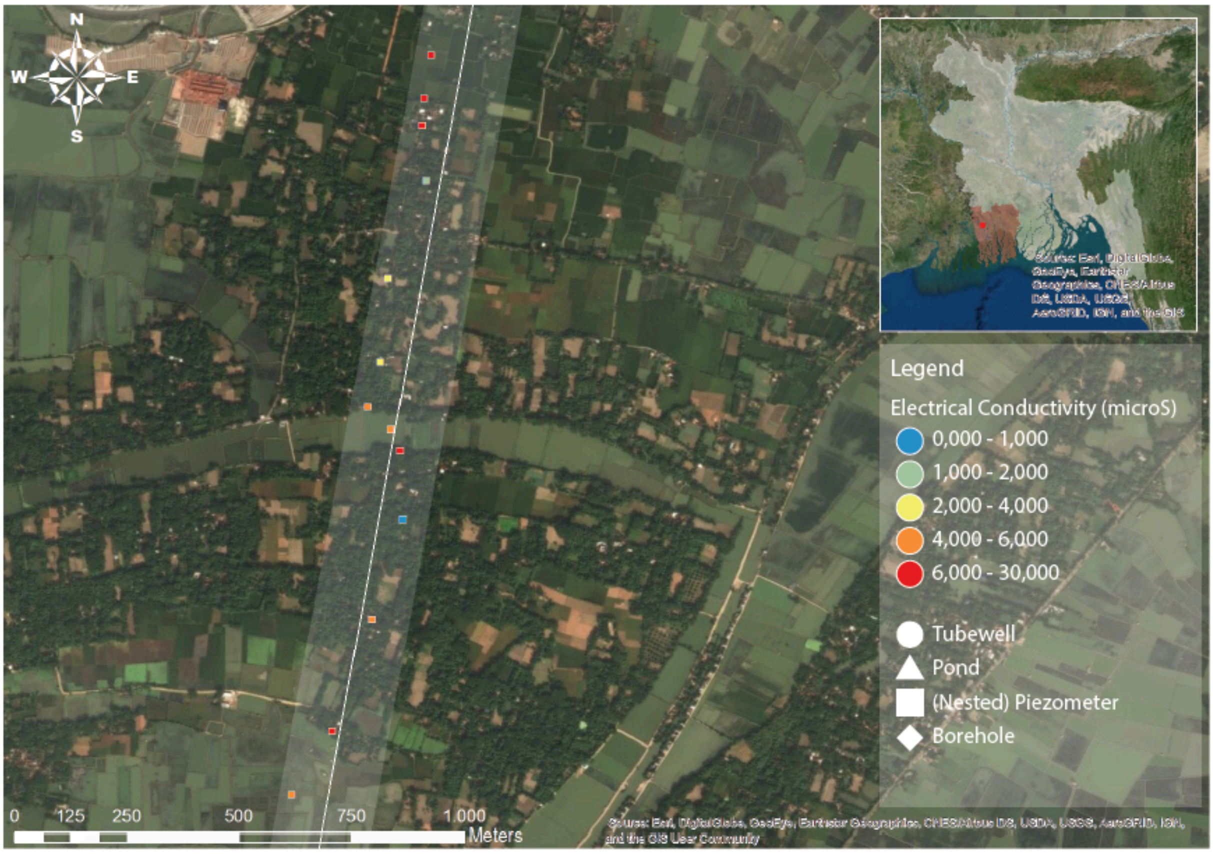

Figure A3: map of the electrical conductivity of piezometers in Assasuni.

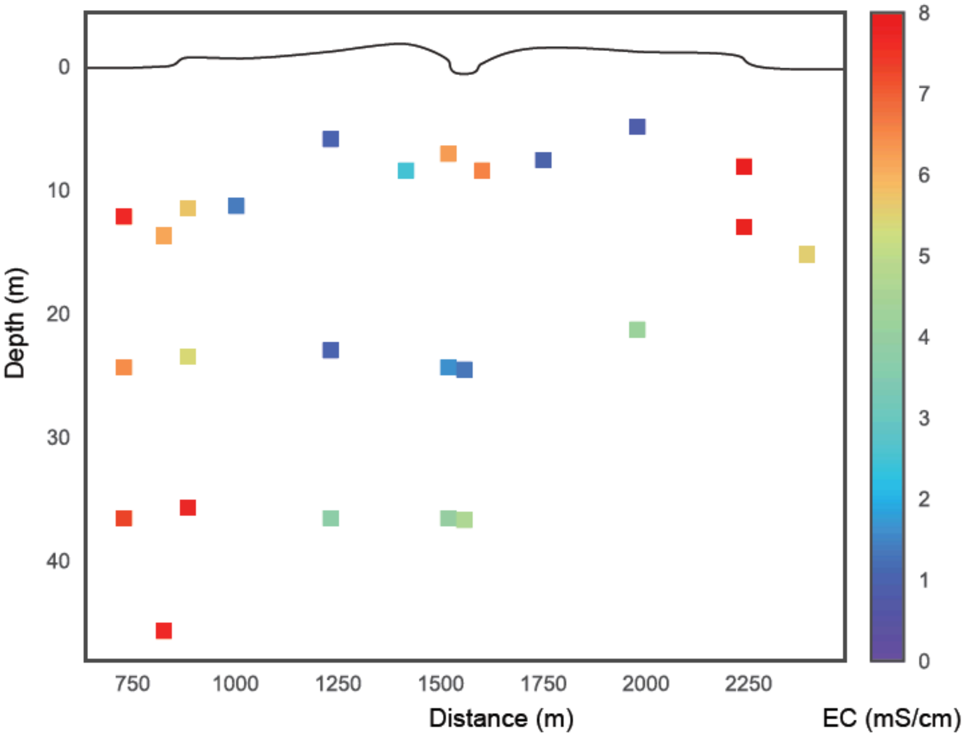

Figure A4: Cross-section of the electrical conductivity of piezometers in Assasuni.

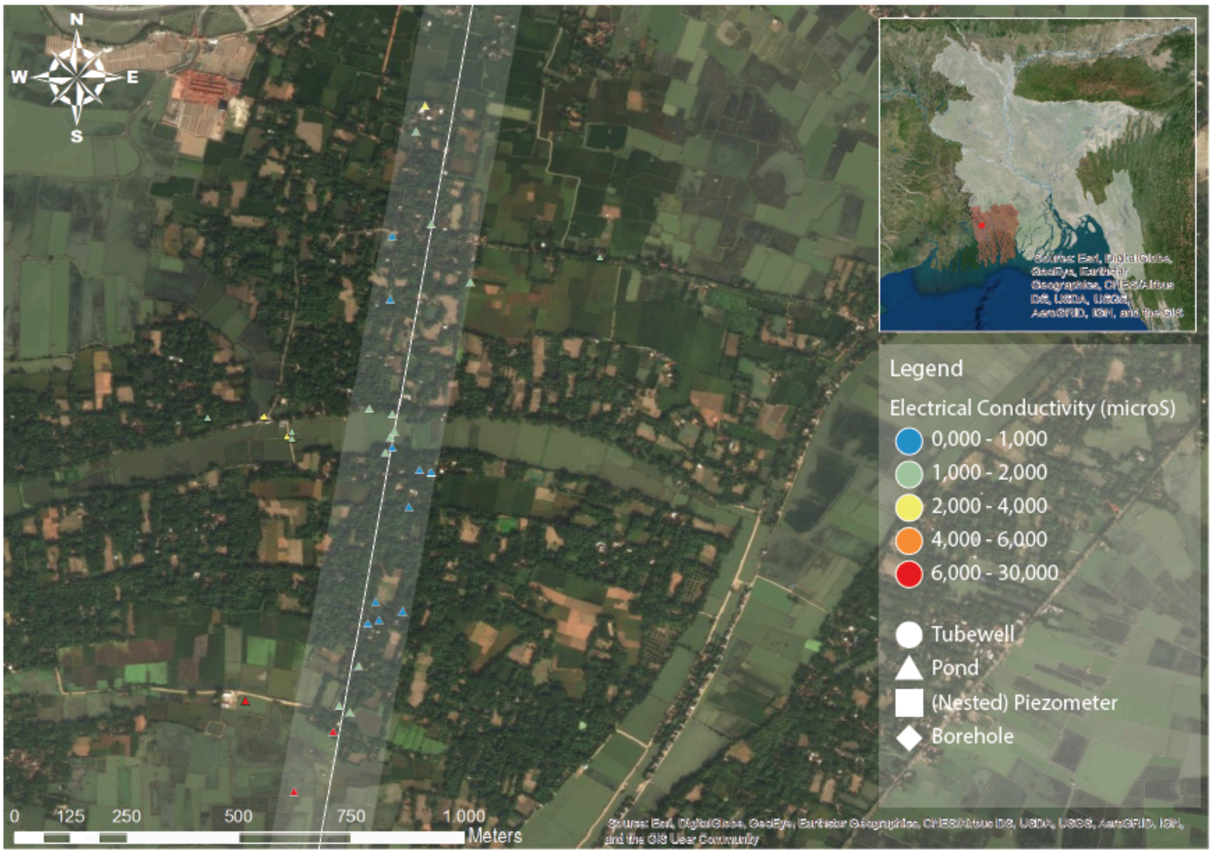

Figure A5: map of the electrical conductivity of ponds in Assasuni.

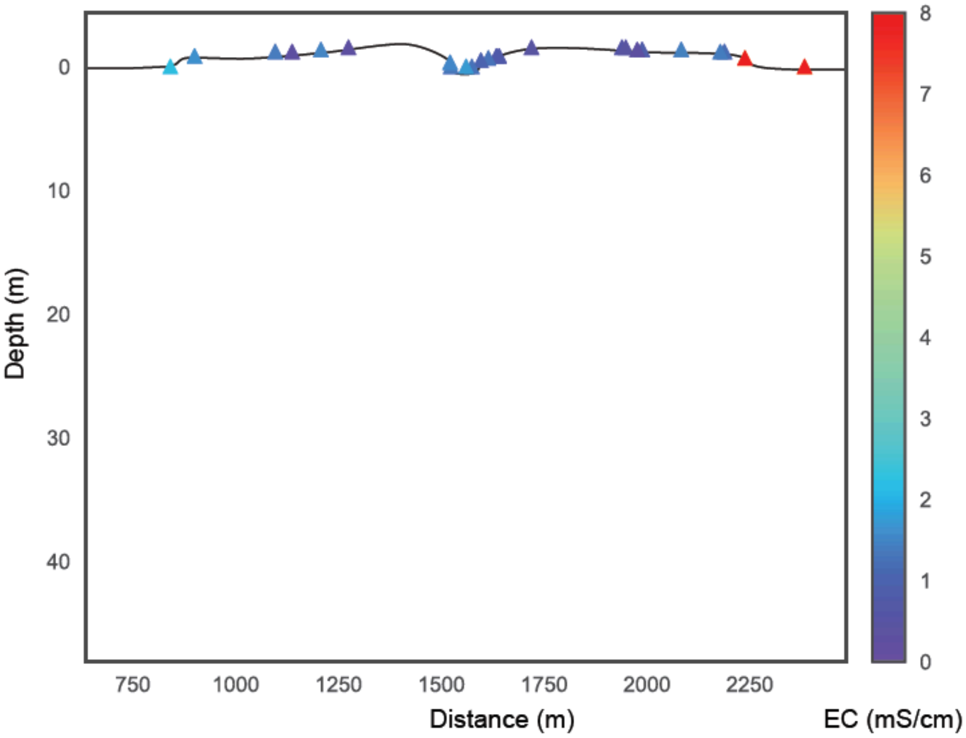

Figure A6: Cross-section of the electrical conductivity of ponds in Assasuni.

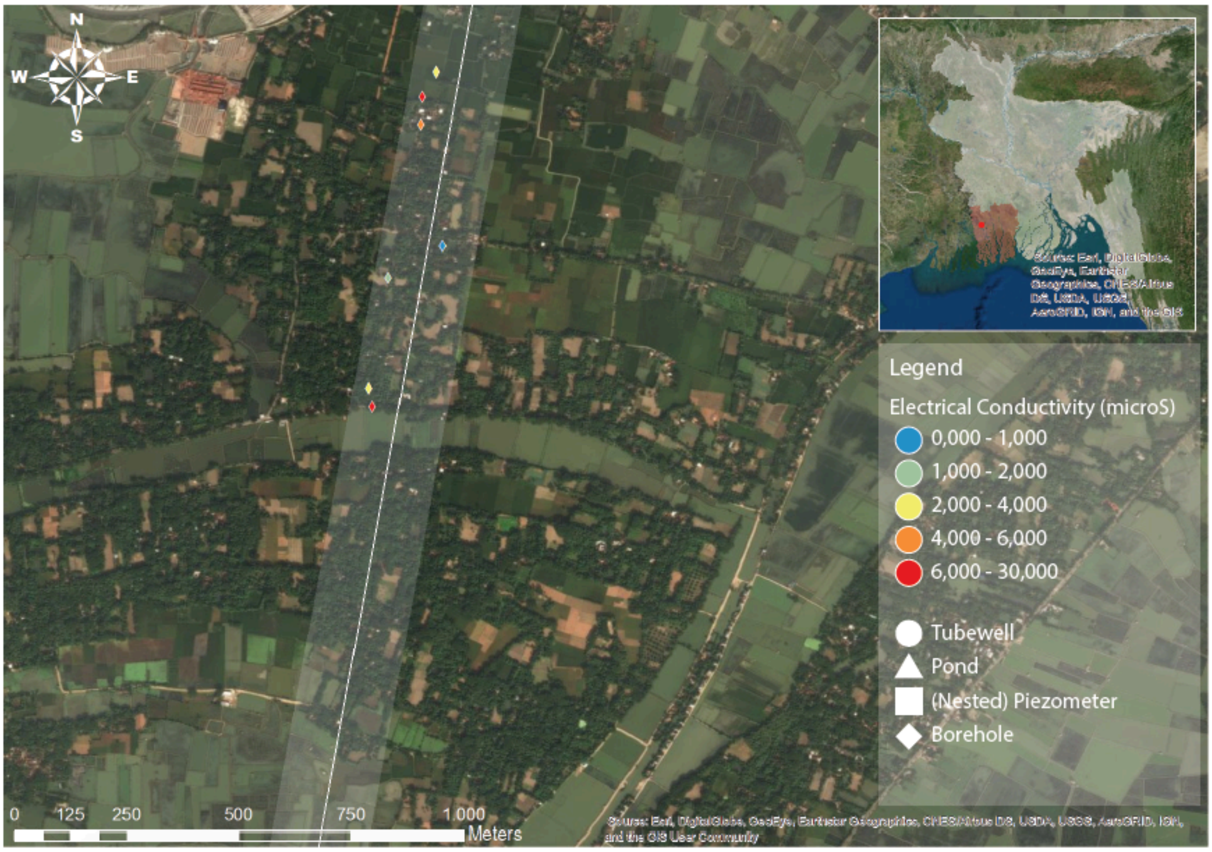

Figure A7: map of the electrical conductivity of boreholes in Assasuni.

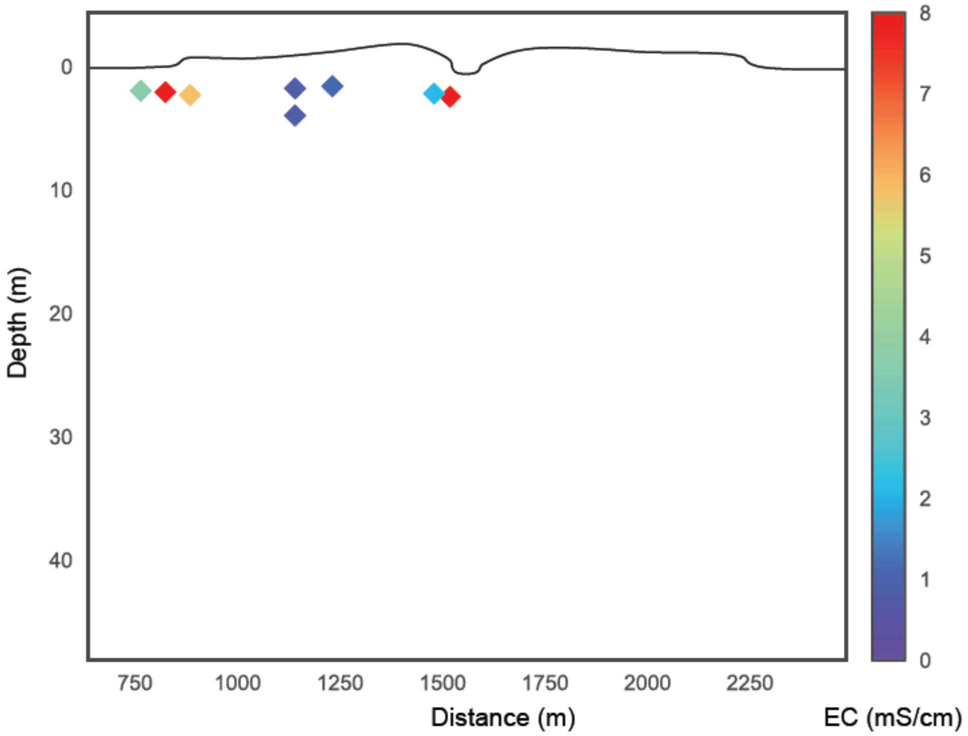

Figure A8: Cross-section of the electrical conductivity of boreholes in Assasuni.