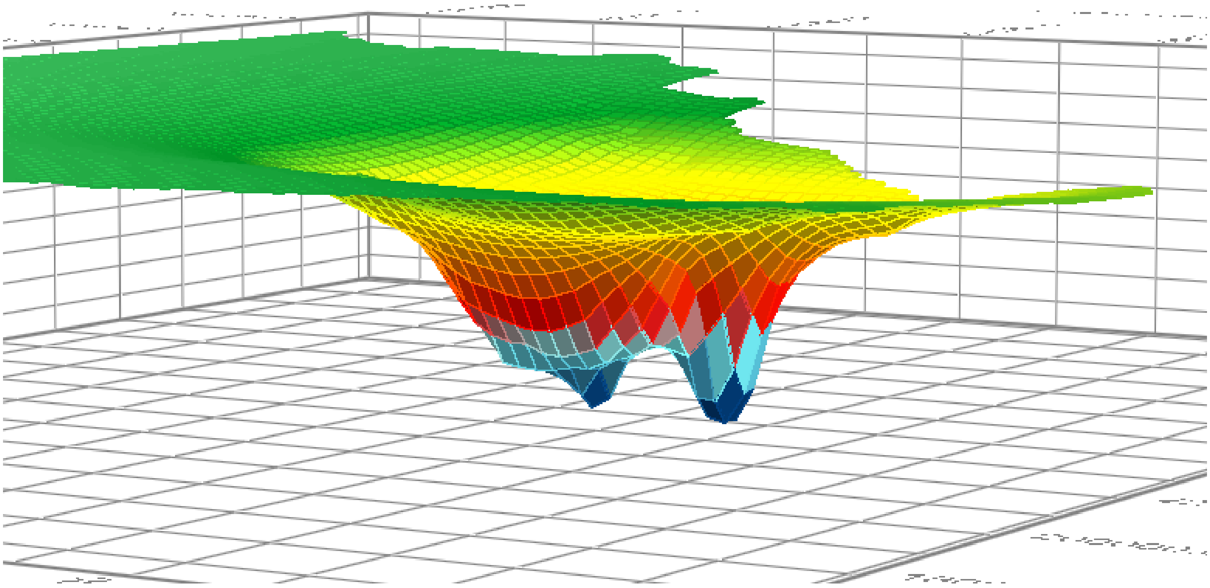
Groundwater model of Dhaka

A study to improve an existing groundwater model of Dhaka and to explore its applications



A thesis submitted to the Faculty of Civil Engineering
of the University of Twente

In partial fulfilment of the requirements
for the degree of
Bachelor of Science

by

Kai M. Hermann

30 June 2016

Groundwater model of Dhaka

A study to improve an existing groundwater model of Dhaka and to explore its applications

Author
Kai Manuel Hermann
K.M.Hermann@student.utwente.nl
+316 211 544 27

Supervisor Bachelor Thesis
H.J. Hogeboom, MSc
University of Twente
h.j.hogeboom@utwente.nl
+31 53 489 4320

Supervisor Internship
J. Kleijer, MSc
Vitens Evides International
Jonne.Kleijer@vitens.nl
+316 301 813 25

Picture on front page: a 3D impression of the final version of model, representing the heads ranging from 0 to -80 meters

Preface

When I first contacted Folkert de Jager for a potential internship in Dhaka, I was motivated by two things: I wanted my thesis project to be about water modelling and I wanted a thesis project abroad. Bangladesh sounded like it had some water engineering trouble where even an insignificant bachelor student can be of essence, and before I knew it I was sitting in the head office of the water supply company in Dhaka.

I was quite honored when given the opportunity for an assignments with such a large extent. After I finished my project, it seemed like there are still infinite possibilities to improve the model further, but nonetheless I was satisfied with the things that were accomplished. For this however I can't just pad myself on the shoulder, but I have some people to thank for this.

First of all I want to thank Jonne Kleijer for his great supervision and dedication to my project, guiding me through the entire process in Dhaka. I would also like to thank Rick Hogeboom for all the critical but fair feedbacks and for helping me answer many of my questions about groundwater modelling, Gertjan de Wit for his occasional private lectures about geology, Sjoerd Rijpkema for helping me deal with the countless bugs in iMOD and Lara Schuijt for helping me improve my poor writing skills. Finally I would like to thank Folkert de Jager and the rest of the staff for enabling me to make this great journey and always making me feel welcome in the office and in Bangladesh.

Dhaka, June 2016

Kai Hermann

Abstract

Dhaka, capital of Bangladesh, has evolved into one of the largest megacities in the world over the past decade. However, this rapid growth caused a water supply issue in terms of both scarcity and water quality. To address this water supply issue in Dhaka, a groundwater model was created to acquire a better understanding of the effects of interventions in the water supply. The aim of this study was to improve the groundwater model and explore its application in a scenario study. To improve the model, input data about the wells, recharge from precipitation and rivers was integrated in the model. Thereafter the heads of the model were fitted to observed groundwater levels by adjusting the vertical hydraulic conductivity, horizontal hydraulic conductivity and the vertical anisotropy. Finally the improved model was applied by computing the effects of three possible policies with the model. The improved input data and calibration resulted in a more accurately illustration of the cone of depression by the model. The cone of depression in Dhaka goes as low as 80 meters below surface level with a radius up to 40 km according to the improved model. The model was able to map precise changes in groundwater level caused by possible water supply policies, making it a convenient tool for the local authorities. While the model is much improved, it is necessary to obtain more reliable and recent data about the wells, rivers, recharge, lithology and permeability to minimize the error of the model.

Table of contents

List of Figures

List of Tables

1. Introduction

Fresh water is at the core of economic and social development; it is vital to maintain health, grow food, manage the environment, and create jobs (World Bank, 2016). Since the surface water is visible and tremendous amounts of money have been spent on building surface water facilities, it's natural to assume it's the world's major source of fresh water. But actually more than 97 percent of the world's fresh water descends from underground resources (Driscoll, 2012). The ground also acts as an excellent mechanism for filtering out pollution, making groundwater the most convenient source for water supply (USGS, 2016). Despite the great importance of fresh water, over 663 million people in the world still lack access to improved drinking water sources (World Bank, 2016).

Bangladesh is one of the most densely populated countries in the world with a population of over 150 million people (infoplease, 2016), and has struggled with water supply issues for many years, in both water scarcity and water quality (Hedrick, 2016). With a combination of a fast growing economy and support from western countries, Bangladesh is however addressing the water supply problem at a large scale, looking for a better future.

The water supply issues in Bangladesh poses the biggest problem in the nation's capital: Dhaka. Dhaka is the economic and cultural centre of Bangladesh and has evolved into one of the largest megacities in the world over the past decade (Kabir & Parolin, 2013). The rapid growth of the population has caused an immense pressure on the water supply of the city (Hoque et al, 2007). The local authority for water supply is the Dhaka Water Supply and Sewerage Authority (DWASA), which abstracts up to 78% of the water supply from underground resources (DWASA, 2013). The domestic abstractions together with all private abstractions result in a total abstraction op approximately 1.5 billion cubic meters from the groundwater each year (Ahmed, 2006). This has resulted in a drawdown up to 70 meters (Hoque et al, 2007) with an annual decrease of 2 meters (Akther et al, 2009). This drawdown of groundwater can eventually lead to drying out the wells (Wada, et al., 2010) and a significant increase in pumping costs (Holierhoek, 2016).

To assist DWASA in making decision with the regard to abstraction of groundwater, a groundwater model was developed for Dhaka. This report will elaborate how this model was improved in order to acquire a better understanding of the effects of interventions in the water supply.

Section 1.1 will give general introduction to geohyrdrology, while section 1.2 will describe the current Dhaka situation and elaborate on the necessity of a model. Finally, section 1.3 will describe the research objective which is addressed in this report.

1.1 Theoretical context of geohydrology in Dhaka

Geohydrology deals with the distribution and movement of groundwater in the Earth's crust. Water infiltrates into the ground through many water sources like rivers or precipitation. The first infiltration of water replaces soil moisture, and, thereafter will slowly infiltrate the ground layers to the zone of saturation (Fetter, 2001). A ground formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs is called an aquifer (Todd et al, 2005). An aquifer is typically composed of sands, gravels and sandstones (Fetter, 2001). An aquitard is a formation of lower permeability that may transmit quantities of water that are significant in terms of regional groundwater flow, but from which negligible supplies of groundwater can be obtained (Hiscock & Bense, 2014). Aquitards are composed of materials with very small grain sizes, such as clay or limestone (Kruseman & Ridder, 1991).

The city of Dhaka is located on a sand pack of circa 5000 meter. Under this sand layer is an impermeable rock layer. The first 1000 meter of this sand pack is most relevant for the drinking water abstraction, because in the lower layers the storage will be too low to have a significant influence on wells (Wit, 2016). There are roughly 3 aquifers below Dhaka: Upper Dupi Tila Aquifer 1, Upper Dupi Tila Aquifer 2 and Lower Dupi Tila Aquifer, illustrated in Figure 1. Most of the water is abstracted from the Upper Dipu Tila Aquifers.

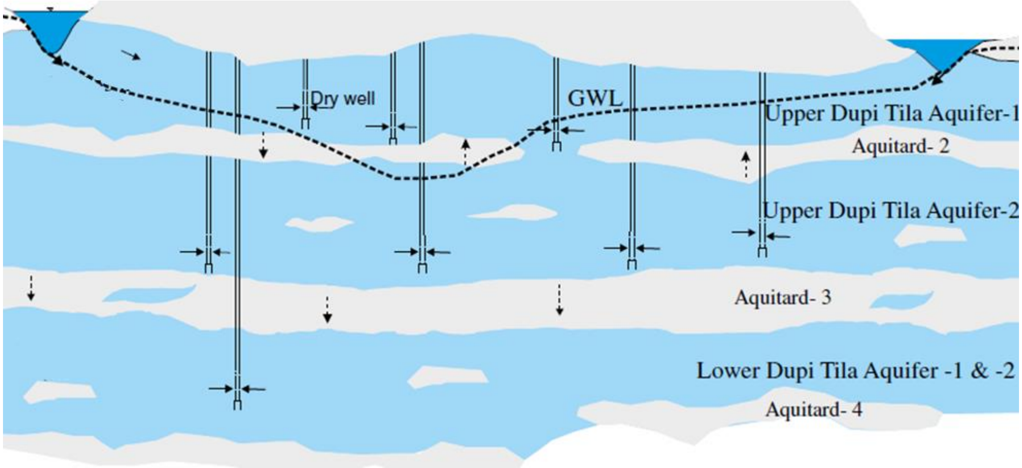


Figure 1: Aquifers (blue) and aquitards (grey) below Dhaka, with several hypothetical deep tube wells inserted in the ground. Dotted line represents the hypothetical Ground Water Level (GWL). Modified from Rahman et al, 2013

The groundwater flows through aquifers can be described with Darcy's law. Darcy's law is a proportional relationship between the instantaneous discharge rate through an aquifer and the pressure drop over a given distance (FracFocus, 2016). Darcy's law is illustrated with the following equation:

$$Q = -K * A * \frac{dh}{dl}$$

where K is the hydraulic conductivity, A the surface area and dh/dl the ratio of the height and the length of the surface. The hydraulic conductivity is used to describe the permeability of an aquifer. This basic formula assumes that the geological material is homogeneous and isotropic, implying that the value of K is the same in all directions. This is however rarely the case in practical situations and this phenomena is described by anisotropy (Todd & Mays, 2005).

The hydraulic conductivity in an anisotropic aquifer is expressed in a horizontal (Kh) and a vertical (Kv) component. These can be described with the following equations (Todd & Mays, 2005):

$$K_h = \frac{z_1 * K_1 + z_2 * K_2 \ldots + z_n * K_n}{z_1 + z_2 \ldots + z_n}$$

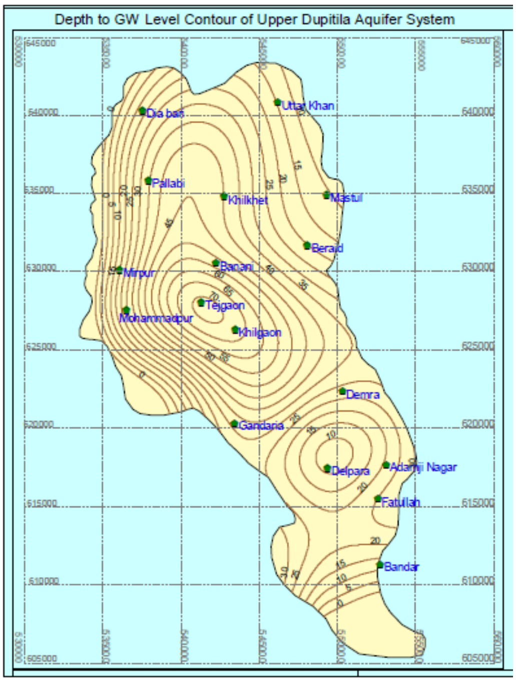
$$K_v = \frac{z_1 + z_2 + z_3}{\frac{z_1}{K_1} + \frac{z_2}{K_2} \ldots + \frac{z_n}{K_n}}$$

where z is the thickness of the layer. Usually the Kh has a higher value than the Kv. A rule of thumb is that the Kv is 10% of the Kh, but this relation can also exceed to much greater differences (Freeze & Cherry, 1979).

Groundwater models are used to establish a better understanding of a geohydrological system and make predictions about how these systems can evolve. A groundwater model combines the flow equations to all attributes of an area. The attributes which are integrated in a model often depend on the available data, but some of the most important attributes are: the thickness, Kv, Kh and anisotropy of an aquifer, the wells, the rivers and the recharge (Kumar, 2015). Groundwater models are commonly used to compute the hydraulic head (further mentioned as “head” in this report). This is a measure of the mechanical energy that causes groundwater to flow, representing the difference between the land surface elevation and depth to water (Fetter, 2001).

1.2 Developments of groundwater in Dhaka

The current drawdown of the groundwater in Dhaka together with the prognosis of the growing population is a problem which has to be tackled to ensure a sustainable future for Dhaka. The causes, effects and solutions for this problem will be elaborated in this section.



A drawdown occurs when the amount of water abstracted from an aquifers exceeds the recharge (Andren, 2014). A large cone-shaped decrease in groundwater level will occur, called a cone of depression.

The cone of depression in 2008 conducted by the institute for water modelling (IWM, 2008) is displayed in Figure 2. This study suggested a maximum drawdown of -70 meters in 2008 with an influence radius up to 5 km. This confirms earlier research by Hoque et al (2007), who also suggested there is a maximum drawdown of -70 meter in 2007 with an influence radius of 5 km. Akther et al (2009) concluded there was a drawdown of up to -55 meters in 2005 with an annual decrease of 2 meters.

Recent research by Wit (2016) however suggested the amount of water which is abstracted from the ground originates for only 5% from the storage, and further is completely accommodated by the recharge from the rivers. Therefore the situation should soon reach an equilibrium with a stable groundwater level, as long as the abstractions stay the same.

With the rapid population growth in Dhaka, the demand for water will increase and therefore the drawdown will also increase. If the drawdown leads to the drying out of wells, this can lead to serious problems of water scarcity. The increasing drawdown will also lead to higher pumping costs and poses the necessity of constructing deeper wells. This can cause serious financial issues for DWASA in the future.

DWASA has studied possible solutions to decrease the drawdown. They conducted a master plan to switch to surface water (DWASA, 2014). This plan is focussed on decreasing the abstractions from the groundwater as much as possible. Another plan is to recharge the aquifers through artificial recharge. Surface water would then be transported to injection wells and injected into the ground (Prodhania, 2016).

Although the causes, the effects and the possible solutions for the problem have been studied, very little measures have been implemented to tackle this problem. Besides the financial problems and the insufficient knowledge in DWASA, one of the main reasons that no measures are implemented is that there are no proper predictions of the effects of any measures for the groundwater problem. A model could serve as the right tool to calculate the effects of any measures and could therefore be a big asset to DWASA.

Vitens evides international (VEI) started developing a base model in 2015 to assist DWASA with geohydrological decisions. The model was constructed in a very short amount of time and is not developed sufficiently to serve as a decision making tool. The model is lacking in reliable input data and calibration. Only if the model is developed further it could be used as a decision making tool in the future for Dhaka.

1.3: Problem statement and research aim

While DWASA has conducted several plans for a sustainable future for Dhaka, it's lacking the appropriate tools to evaluate these plans. The most convenient tool to predict the effects of any interventions in the water supply is a groundwater model. For this reason Vitens Evides International (VEI) started to develop a groundwater model of Dhaka. This base model is relatively simplistic and in need of improvement. The aim of this study is: *"Improve the groundwater model of Dhaka in order to acquire a better understanding of the effects of interventions in the water supply."*

This study will be focused on answering two main questions. To help answer these questions, five sub-questions are formulated, which are divided into several sections.

Main questions

1. How can the current groundwater model of Dhaka be improved?
2. What will be the impact on the groundwater level if new water supply policies are implemented?

Sub-questions

1. How can the private wells be integrated more accurately in the model?
    a. What are the locations of the private wells?
    b. How much water do the private wells abstract?
2. How can the surface water be integrated more accurately in the model?
    a. How can the water bodies in Dhaka be integrated in the model?
    b. How can the river depth be improved?
3. How can the recharge from precipitation be integrated more accurately in the model?
    a. What is the amount of precipitation around Dhaka?
    b. What is the potential evapotranspiration around Dhaka?
    c. What is the difference in soil types around Dhaka?
4. How can the model be improved due to calibration?
    a. How can the vertical hydraulic conductivity be improved?
    b. How can the horizontal hydraulic conductivity be improved?
    c. How can the vertical anisotropy be improved?
5. How will the possible future scenario's look like according to the model?
    a. What is the effects on the groundwater level of the DWASA master plan?
    b. What is the effect on the groundwater level if all there are no more abstractions from the industry?
    c. What is the effect of recharging the aquifer artificially?

1.4 Base model

The existing groundwater model (referred to as "base model" in this report), will be improved in this study. The model was developed in December 2015 by Sjoerd Rijpkema. This section will provide a brief description of the model.

The extent of the model is 158x216 km with a resolution of 100m (Figure 3). The Padma and Meghna River are forming the east, south and west boundaries of the model. The northern boundary is an open boundary 150 km north of Dhaka. There is also a detail boundary specified around the region of Dhaka. The details about lithology and water abstractions are much more detailed in this area. The lithology for the remainder of the model is based on a bigger model of Bangladesh by Michael & Voss (2009).

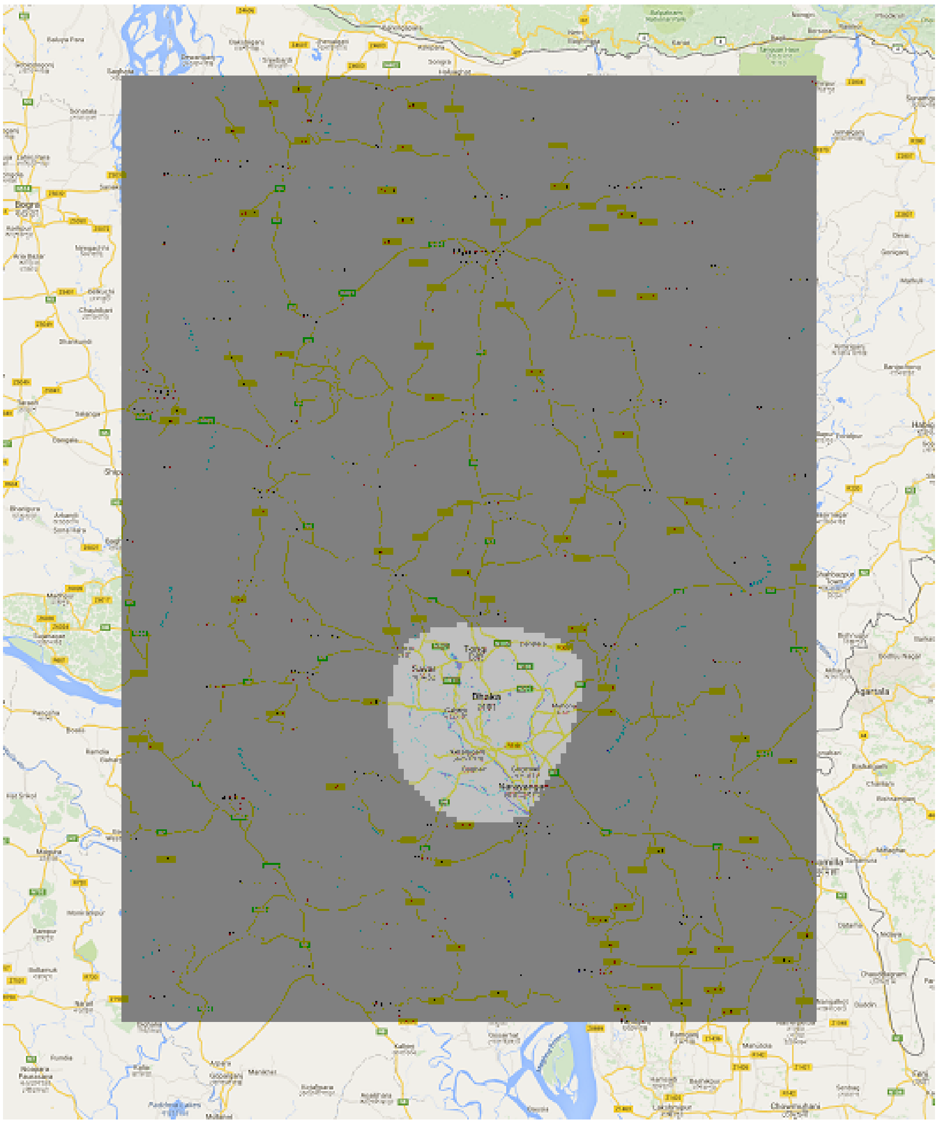


Figure 3: Extent of the model (grey) with the detail are (circle inside grey zone). Al maps in the model were made at this extent. Note that this extent does not represent the boundaries of the model

To determine the geological formation in the detail area, the information of 231 digital bore logs is interpolated, neglecting all layers smaller than 2.6 meters. This resulted in 6 layers. The Michael & Voss (2009) model adds 3 more layers to the base model. The detailed area nested in the larger model is displayed in Figure 4.

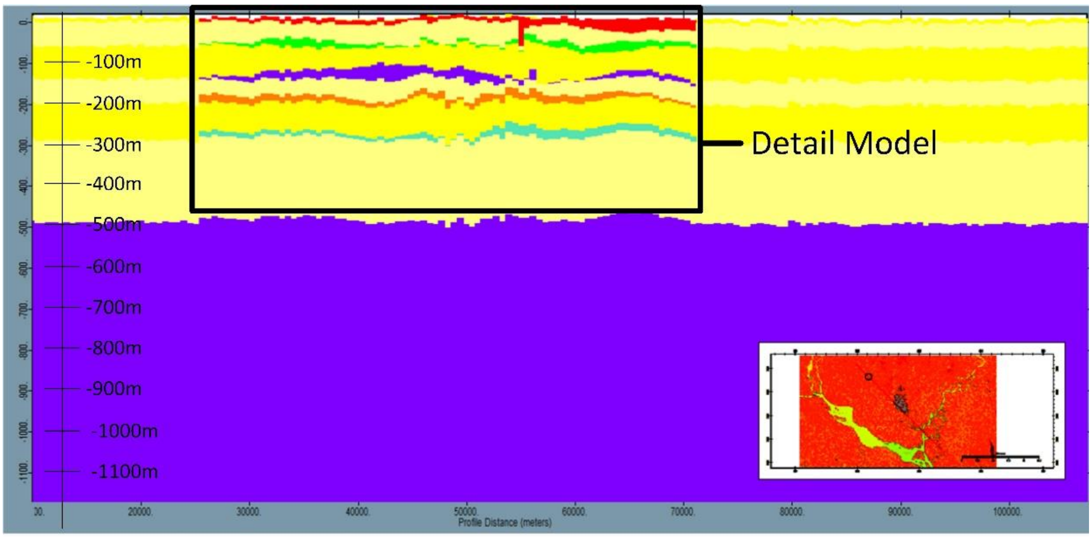


Figure 4: Cross section of model layers. Detail model represents aquifers/aquitards within a radius of 30km of Dhaka. Within the detail model coloured layers represent aquitards and yellow layers represent aquifers. Outside of detail boundary no aquitards are present.

The elevation of the soil is based on STRM elevation maps (2015). This elevation represents the top layer of the model.

The recharge of the model is assumed to be 1.5 mm/day over the entire extent. This represents the amount of water which percolates into the ground as a result of precipitation.

The rivers are derived from polygon shape files received from the Institute of Water Modelling (IWM, 2015). All rivers are assumed to have a depth of 10 meter below surface level.

There are 546 wells of DWASA integrated in the model with a total abstraction of 1.5 Mm^3/year (DWASA, 2013). This abstraction was evenly divided over all DWASA wells.

The K-values and vertical anisotropy are based on standard literature. The Kv only present in the aquitards and the Kh is only present in the aquifers. Although the values inside the detail area are heterogeneous, the differences were relatively small. Therefore the K-values will be treated as constant values in this thesis.

Table 1: Kv and Kh values for model. The aquifers represent the Kh values and the aquitards represent the Kv values. The values the K-values inside the detail boundary were based on the bore logs and heterogeneous. Outside the detail boundary were roughly estimated and homogeneous.

Layer	Hydraulic conductivity inside detail boundary (m/day)	Hydraulic conductivity outside detail boundary (m/day)
Aquifer 1	10.00	17.30
Aquitard 1	0.01	-
Aquifer 2	10.00	17.30
Aquitard 2	0.01	-
Aquifer 3	15.00	17.30
Aquitard 3	0.01	-
Aquifer 4	17.30	17.30
Aquitard 4	0.01	-
Aquifer 5	15.00	17.30
Aquitard 5	0.01	-
Aquifer 6	29.10	17.30
Aquifer 7	17.30	17.30
Aquifer 8	17.30	17.30
Aquifer 9	17.30	17.30

2. Methods and Data

To improve the groundwater model of Dhaka and acquire a better understanding of the effects of interventions in the water supply, three major phases were aligned to conduct the research. In the first phase the input data of the model was improved. The new input data had to describe more accurate information about the wells, recharge from precipitation and rivers in the model. In the second phase the model was calibrated, by fitting the flow parameters to observed data. In the third phase the model was tested by computing several water supply scenarios.

The sections in phase 1 and phase 2 are separated in two subsections: data and method. The data sections will describe which new data was acquired. The method section will describe how this data was adjusted to serve as a suitable input for the model.

Phase 1: Improvements to Input Data Model

2.1 Improvements to input data of wells

The base model considers the abstractions of the DWASA wells and neglects all other wells, while in reality approximately half of the abstractions in Dhaka originate from private wells. The groundwater level strongly depends on the wells in the model and therefore the locations and abstractions of the private wells in Dhaka were added to the model.

To integrate new wells in the model, the coordinates, abstraction and screen depth of a well had to be known. The wells can then be integrated in the model using the well-package of iMOD (see Appendix C1: *Well package*).

2.1.1 Data private deep tube wells

A private deep tube well (PTW) is a deep tube well which abstracts water from the ground and is neither constructed nor operated by DWASA, but is located within the service area of DWASA. These PTWs are either registered or are not registered and thus illegal. All relevant data which could be acquired about the PTWs will be described in this section.

There are 2198 PTWs in Dhaka, including 309 industrial wells and 1889 domestic and commercial wells. This is based on the costumer information about all registered PTWs (DWASA, 2015). It is assumed that these numbers also represent all illegal PTWs because otherwise there is no reliable indication for the illegal wells.

The total abstraction of DWASA is 750 Mm^3/year. This is based on the annual report of DWASA from the year 2012-2013. Since this is the most reliable indication of abstractions in Dhaka, all other abstractions are based on their ratio with the DWASA wells.

The ratio of the abstraction of the DWASA wells and the PTWs is respectively 100:95 (Ahmed, 2006). The ratio of the PTWs between the different city districts are also assessed by Ahmed (2006) and will be elucidated in section 2.1.2: Method of integrating well data. The ratio of the abstraction of the DWASA wells and the industrial PTWs is 5:1 (FAO, 2014).

Because there is only global data about the wells and no detailed data about individual wells, it's assumed all industrial wells have the same abstraction and all domestic and commercial wells have the same abstraction. Using this as the basic principle it was also assumed the amount of wells corresponds with the amount of abstraction, meaning a region where the total abstraction is high, the number of PTWs is also high, and vice versa.

The most important numbers which were derived from this data and assumptions are displayed in Table 2.

Table 2: Number of wells and abstractions of all PTWs and DWASA DTWs in Dhaka

Well type	**Number of Wells**	**Total Abstraction (Mm^3/y)**
All Private Wells	2198	712.5
Industrial Private wells	309	150.0
Commercial and domestic private wells	1889	562.5
DWASA wells	546	750.0

2.1.2: Method of integrating well data

The commercial and domestic wells are divided over 7 city districts of DWASA, zone 1 to 7. The abstractions of these zones are based on Ahmed (2006). These abstractions are normalized to percentages. These percentages are multiplied with the total amount of commercial and domestic wells, distributing the wells according to Table 3.

Table 3: Distribution of the Domestic and Commercial wells over 7 DWASA zones, quantified in the percentage of the total amount of wells in each zone and the resulting amount of wells in each zone.

Zone	**Percentage of total amount of wells (%)**	**Number of wells**
1	7.61	144
2	1.53	29
3	9.19	174
4	19.17	362
5	17.03	322
6	5.05	95
7	40.42	764
Total	*100%*	*1889*

To estimate the locations of the industrial wells, a map (Figure 5) of the areas of the garment and textile industry was used. The used data was limited to the garment and textile industry because these outweigh the other industries around Dhaka significantly (CUS, 2010).

To quantify the amount of wells in each of the industrial areas, the density of the wells of a certain surface is estimated by using Figure 5. This is done by a simple visual inspection, distinguishing the areas where the density of the industry looks high, medium or low. These were quantified as 3, 2 and 1, respectively. These quantities represent the ratios of the areas, meaning the PTWs in a “high” area will be three times as dense as in a “low” area. With a simple formula the amount of wells per area is then determined. This formula is discussed in Appendix D: *Wells*.

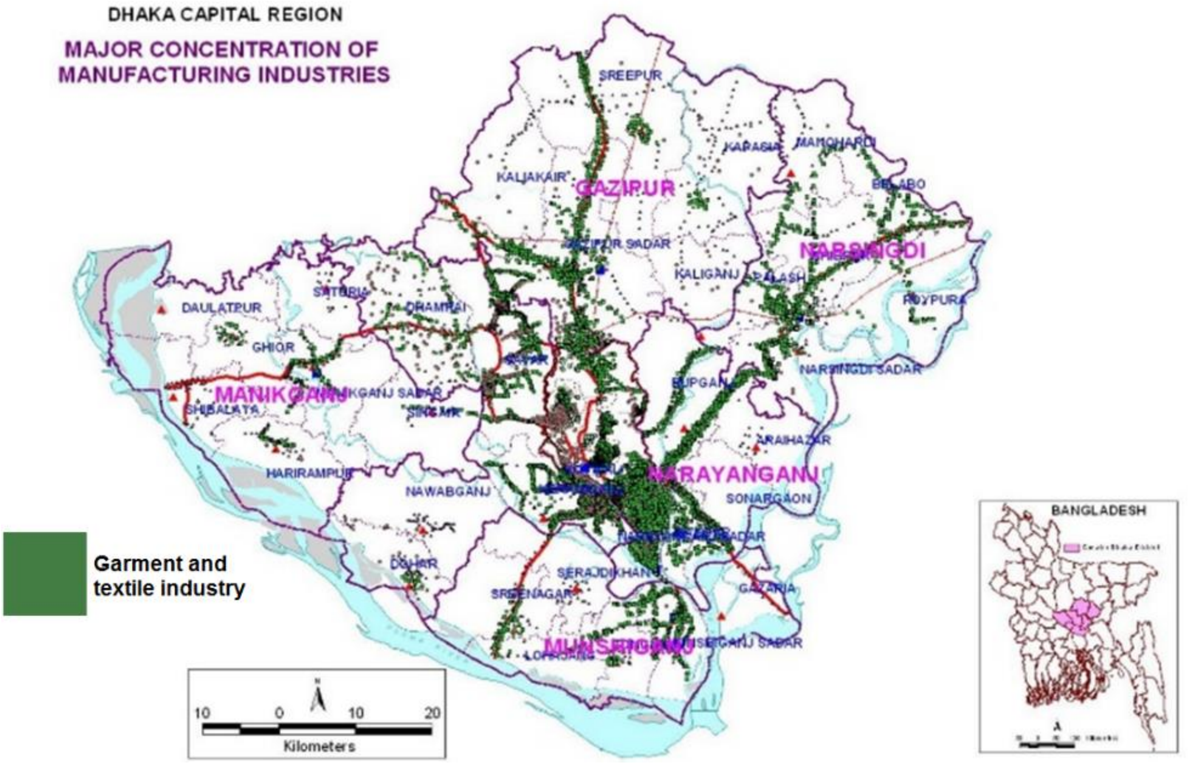


Figure 5: Location of garment and textile industry around Dhaka (CUS, 2010). By visually inspecting the data, six major areas of industry, where the industrial wells will be located, were delimited.

To make the wells a suitable input for the model, the coordinates, abstraction and screen depth had to be specified. To estimate the coordinates the amount of wells were distributed over shapefiles which represented their corresponding area, using the “*create random points”* function in ArcMap. To distribute the wells evenly over the areas, the minimum distance between wells was set to be as high as possible by trial and error. To estimate the screen depth, all wells were assumed to subtract water from the fourth layer of the model, because this is the most convenient layer to abstract water from.

2.2: Improvements to input data recharge from precipitation

The base model simplified the recharge from precipitation to be 1.5 mm/day over the surface of the entire model. This is an inaccurate assumption because it is not supported by any observed data and in reality the water will percolates at different rates on different soil types.

The recharge from precipitation is integrated in the model using the recharge package of iMOD. The recharge package defines the quantity of water from precipitation that percolates to the groundwater by one raster map. Therefore the amount of water which percolates to the groundwater has to be known.

2.2.1: Data for precipitation, evapotranspiration and soil types

To obtain a better estimation of the recharge from precipitation in the study area, data of the precipitation, evapotranspiration and soil types had to be collected.

The precipitation data of 5 stations around Dhaka in 2015 was collected (Figure 4). The daily potential evapotranspiration is available from 1993 until 2013 (BMD, 2013). Although it is preferable to have data from the same year, in this case the potential evapotranspiration of the most recent year (2013) is used.

The data of the soil types around Dhaka was obtained by visually inspecting the satellite images (Esri, et al., 2016). The Spatial Layout is divided in 3 surface categories: Urban, Sub-Urban and Agriculture. These categories were chosen because it was convenient to distinguish the highly dense build-up area of Dhaka (urban) and the farmlands (agriculture). Everything in between is classified as sub-urban. An example of the areas is presented in Figure 7. The resulting spatial layout is presented in Figure 20 in Appendix F: *Spatial layout around Dhaka*. Because mapping the spatial layout is a time consuming process, only the different spatial classes around Dhaka were mapped. All other values were assumed to be Sub-urban.

Figure 6: The 5 stations, Gopalganj, Kamerkhali, Terash, Netrokona and Nikli, around Dhaka from which precipitation data is used. The precipitation data is measured every minute from July 2014 until November 2015 (BMD, 2015)

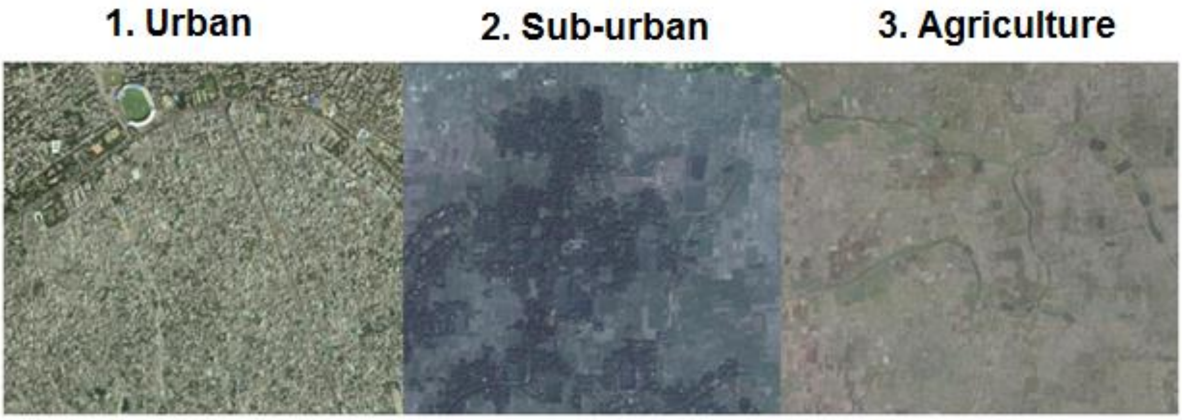


Figure 7: spatial areas around Dhaka (Esri, et al., 2016). 7.1 displays mainly urban structures such as houses, offices, shops etc., 7.2 displays some houses and shops (usually surrounded by a lot of trees) as well as farmland 7.3 displays only farmland.

2.2.2: Method of integrating recharge from precipitation

The Recharge is calculated using the water balance method mentioned in Appendix B: *Water balance*. Note that not the actual recharge is calculated, but only the recharge from precipitation. Therefore the net flux of any water entering or leaving the region other than precipitation (q_N) will be neglected since this not related to precipitation.

To simplify the water balance further the surface runoff (q_s) and the groundwater contribution to runoff (q_b) are neglected. These are replaced by an infiltration factor (IF). The IF assumes that the fraction of the precipitation lost to runoff and evapotranspiration depends on the land use, this will be discussed later in this section.

The actual evapotranspiration is not known, therefore the potential evapotranspiration (PET) is used. The PET is defined as the amount of evaporation that would occur if there is no limitation to soil moisture. Assuming the soil moisture will have either evaporated or infiltrated within 1 hour, it's estimated the PET will have an effect during and until 1 hour after precipitation.

In the end the recharge from precipitation is calculated with the equation:

$$R = IF * (P_{t1} - PET_{t1} + P_{t2} - PET_{t2} \dots P_{tn} - PET_{tn})$$

Where IF is the infiltration factor, P_{t1} is the precipitation in time interval 1, PET_{t1} is the potential evapotranspiration in time interval 1 and *tn* is the time interval 1 hour after the last time interval where precipitation occurred.

With the provided data the recharge with IF=1 was calculated first for the 5 stations. The resulting recharge is presented in Table 4. With a nearest neighbour interpolation the IF=1 recharges are rasterized, the resulting map is presented in Figure 19 in Appendix E: *Recharge from precipitation*.

Table 4: Calculated recharge (in mm/day) at different precipitation stations for IF=1

Station	**Recharge (mm/day)**
Gopalganj	2.38
Kamarkhali	3.45
Nikili	1.12
Netrokona	3.60
Tarash	2.10

The IF of the different soil types is based on a study about recharge for different soil types (MDE, 2009). The resulting IF is presented in Table 5.

Table 5: Infiltration factor of the different soil types around Dhaka. The IF of the Sub-Urban soils is maintained to be 1, while the other IFs are adjusted according to the ratio of the MDE study.

Spatial Class	**Soil type**	**Infiltration MDE (2009)**	**IF (-)**
Agriculture	Silt Loam	0.52	1.93
Sub-Urban	Sandy Clay Loam	0.27	**1.00**
Urban	Clay Loam	0.17	0.63

To calculate the recharge from precipitation which will serve as the model input, the recharge map for IF=1 (Figure 19) is multiplied with the infiltration factors according to the values in Table 5 and Figure 20.

2.3: Improvement of input data of rivers

The base model simplifies all rivers to have a constant depth of 10 meters and all river bodies in Dhaka are neglected. This has to be improved because the actual depth of the rivers is not 10 meter and because there are many water bodies in Dhaka.

The rivers can be integrated in the model using the river package of iMOD. The river package defines the locations of the rivers through raster maps. The values of the cells describe the height of the rivers. Each river is integrated with one raster map for the top of the river and one raster map for the bottom of the rivers. The interaction of the rivers with the underlying aquifers is then described by the conductance and infiltration factor, which are constant values for the entire raster map. More information about how the rivers are modelled in iMOD can be found in C2: *River package*.

2.3.1: Data for rivers

It is necessary to classify different classes of rivers, which have approximately the same values for the conductance and infiltration factor. For this data from an earlier study collected by Hoogendoorn (2013) was used. These classes were based on the resistance. The resistance illustrates how well a river interacts with the underlying aquifer and can be used to calculate the infiltration to the aquifer. In this case the water of the Class 1 rivers will infiltrate relatively easy in the ground while class 2 and 3 infiltrate much less. Rijpkema (2015) changed these values to be more convenient for the model, the same classes for the rivers were maintained however. The values for the resistance are presented in Table 6. These values are based on the principle that sediment will precipitate on the river bedding making the river more resistant. A large river where the flow rate is much higher will transport the sediment rather than allow it to precipitate on bedding, making the river thus less resistant.

Table 6: Resistance of rivers (in days) in Bangladesh for 3 classes based on the classification of Hoogendoorn (2013) and the classification of Rijpkema (2015)

Class	Resistance according to Hoogendoorn (2013) (days)	Resistance according to Rijpkema (2015) (days)
Class 1 (Large Rivers)	1	1
Class 2 (Medium Rivers)	10000	5
Class 3 (Small Rivers)	50000	50

The Bangladesh Water Development Board provided cross sections of the rivers (BWDB, 2009). These are presented in Appendix G: *Cross sections of rivers*. To estimate the locations of the rivers the shapes of the rivers were determined using shapefiles of the rivers provided by IWM (2015), which accurately display the shapes of the rivers.

2.3.2: Method of estimating depths of rivers

To estimate the depth of the rivers it was assumed the rivers where rectangular trays. The process of estimating the depths of the rivers is presented in Figure 8.

To integrate the new river depths in the model the rivers had to be rasterized. The top of the rivers were conceived by clipping the shapefiles of the rivers from an elevation map (SRTM, 2015). Therefore it was assumed the top of rivers will be on the surface level. The bottom of the rivers was conceived by subtracting the depth of the rivers from the raster map of the top of the rivers.

The river conductance and infiltration factors of the different classes were maintained to be the same as assumed earlier by Rijpkema (2015).

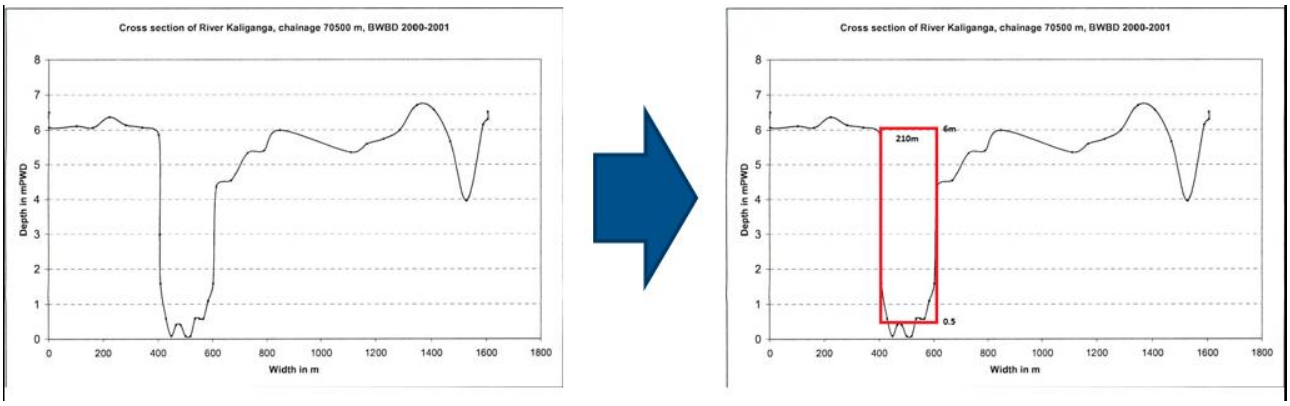


Figure 8: The process of estimating the depth of the river is done by drawing a rectangle in the cross section of the river. A rectangle was drawn around the shape of the river bed, and the height of the rectangle was assumed to be the depth of the river. Height is displayed in meters.

Phase 2: Calibration

2.4: Calibration of the model

After the input data of the model was improved, the model was fitted to observed data. The base model was roughly calibrated by comparing the cone of depression with literature. The model was however not fitted to any observed data in Dhaka.

The calibration is performed with the parameter estimation package of iMOD (iPEST). The basic principle of the iPEST package is that the computed heads are compared to the observed heads. The difference between the heads is then minimized by adjusting certain parameters in the model. The underlying theory of iPEST function and an explanation of the various settings are discussed in Appendix C3: *iPEST Package*.

In this section, the definition of calibration is maintained to be: "*estimation the optimal parameter using the iPEST function*".

2.4.1: Observed data for calibration

The model was calibrated by using the static water level (SWL) of the DWASA wells in Dhaka. The static water level represents the head in a well and is based on 3 datasets:

1. A dataset of measurements in the wells surrounding Dhaka (BWDB, 2014)
2. A dataset of measurements by DWASA performed when the construction of a well is finished (DWASA, 2015)
3. A dataset of extra measurement in the wells of North-Dhaka once pumps are replaced or extra column pipes are added (DWASA, 2016)

Because the groundwater level is decreasing each year, it is necessary that all SWLs originate from a single year to give a good representation of the water table. For this reason all SWLs have to be derived to a single year.

The first dataset contained measures of 59 wells around Dhaka. These wells were measured every week for several years, but there are however many cases where data is missing for several weeks. The SWLs of the week of the 24th of March 2014 were chosen to be used as input for the calibration. This decision is based on 2 reasons. Firstly 2014 is a recent year and can display the current situation relatively well. Secondly there is no data missing in this week while there is a lot of data missing in other recent years.

The second and third datasets provide a representation of the SWLs of several years in Dhaka. The SWL is measured every time a well was replaced. The replacement-well will however not be at the exact same location. There are about 2 to 4 measurements from different years available for each location.

To derive the wells of the second and third dataset to a single year, an inter- or extrapolation has to be conducted. When inspecting the data sets, it clearly indicates a decrease in the SWL, which is also supported by several studies mentioned in the introduction. The data also creates the impression that the SWL is decreasing linear since 2004. If the decrease is indeed linear, the SWLs can easily be inter- and extrapolated by assuming a linear decrease.

To prove whether the water level decreases linear, a chi-square test was performed to test the following hypothesis: "*The SWL at the locations of the wells decreases linear*". If the hypothesis is true the SWLs can be derived to a single year. If the hypothesis is not true and the SWLs cannot be derived to a single year, only the data which is actually measured in a single year will be used. The conditions for the chi-square test are:

- There are at least 3 different datasets available at 3 different points in time
- All measurements used for the test are taken in between 2004 and 2016

The SWLs are derived using the following equation:

$$a = \frac{SWL_{mr} - SWL_o}{t_{mr} - t_o}$$

$$SWL_c = a * (t_c - t_o) + SWL_o$$

Where a is a linear interpolation factor, SWL_{mr} is the most recent measurement, SWL_o the oldest measurement (but not older than 2004), $t_{mr} - t_o$ is the amount of days between the measurements and SWL_c is the computed SWL at time t_c. The computed SWL is then compared with a measurement at the same date according to the chi-square methodology:

$$\chi^2 = \frac{(SWL_m - SWL_c)^2}{SWL_c}$$

Where SWL_m is the measured SWL at the same time t_c. The results of the chi-square test are presented in Table 7 and the entire test is presented in Appendix H4: *Chi-square test*. The test indicates that the hypothesis can be accepted according to the chi-square criterion (Robinson, 2004), and it can be assumed there is a linear decrease in groundwater level since 2004.

Table 7: Results of the chi-square test, which was conducted to test whether the SWL of a well decreases linear over time.

Chi-square test	**value**
SUM CHI square	23
Maximum allowed value	79
Number of measurements	60
Number of degrees of freedom	57

2.4.2: Method of calibration

The parameters which are calibrated are the horizontal hydraulic conductivity (Kh) of layer 1 to 9 and the vertical hydraulic conductivity (Kv) of layer 1 to 6 and the vertical anisotropy (VA) of layer 1 to 9 inside the detail area.

The amount of parameters which were calibrated was minimized to these three because of the limited amount of time available. The decision for these parameters was based on the sensitivity of the parameters. The sensitivity analysis is elaborated in Appendix H3: *Parameter estimation: sensitivity analysis*.

The initial multiplication factor is always set to 1.0. Once a calibration step is performed this factor should be adjusted to the optimal value. The multiplication factor does however not work properly with the appointed zones causing an error in the iPEST simulation. For this reason the adjustments for the values after a iPEST simulation were done manually, meaning the IDFs and constant values in the simulation were changed to the optimal values according to the iPEST simulation.

The size step, minimum, and maximum multiplication factors, differed for each iPEST simulation. The size step was usually about 10 – 20% of the maximum multiplication factor. The minimum and maximum multiplication factors of Kh and Kv were set according to the acceptable values of these parameters. These acceptable values were based on a table from as Groundwater Hydrology (Todd & Mays, 2005), displayed in Table 8.

Table 8: Representative values of Hydraulic Conductivity for different soil materials. Type of measurement indicates a repacked sample of an aquifer (R) or vertical hydraulic conductivity of an aquitard (V)

Material	**Hydraulic conductivity (m/day)**	**Type of measurement**
Sand, coarse	45.0000	R
Sand, medium	12.0000	R
Sand, fine	2.5000	R
Clay	0.0002	V
Limestone	0.9400	V

The Kh values will be allowed to range from 2.5 to 45 and the Kv values will be allowed to range from 2e-4 to 0.94. These values seemed to be realistic values for these parameters based on the literature, there is however no regional data of Dhaka used to validate the results. There were no reliable values found for the VA. The VA was therefore simply allowed to range from 1% to 100% of the initial values in the base model.

Further settings of the iPEST simulation which were not based on any literature but were solely set to keep the simulations for the calibration as simple and time efficient as possible. These settings are discussed in Appendix H1: *iPEST simulation: general settings*.

Phase 3: Scenarios

2.5: Scenario study

Once the model was fitted to the observed data, it could be used estimate possible scenarios in Dhaka. Three scenarios were computed which could be relevant policy changes for DWASA.

2.5.1: DWASA master plan scenario

The first scenario is based on a master plan made by DWASA and IWM, which involved the plan to shift to surface water for a large proportion of the water supply (DWASA, 2014). The amount of groundwater abstracted from the ground would then change from 750 Mm^3/year to 460 Mm^3/year. To compute this scenario all DWASA wells will abstract 61% of the current abstractions.

2.5.2: Industry stops abstracting water scenario

The second scenario is based on the idea that the industry could shift to another water source. The industry is currently using clean water, while many processes could be performed with less quality water. This scenario proposes the possibility of banning the industry from using clean drinking water and switching to surface water for example. To compute this scenario, all industrial wells (discussed in section 2.1) will stop abstracting water from the ground.

2.5.3: Artificial recharge scenario

Recharging the aquifers artificially with surface water is a hot topic to solve the problem of the declining water table in Dhaka. Prodhania (2016) studied the possible amount of service water which could be injected into the ground through several injection wells throughout Dhaka. The coordinates of the wells and the corresponding potential recharge are displayed in

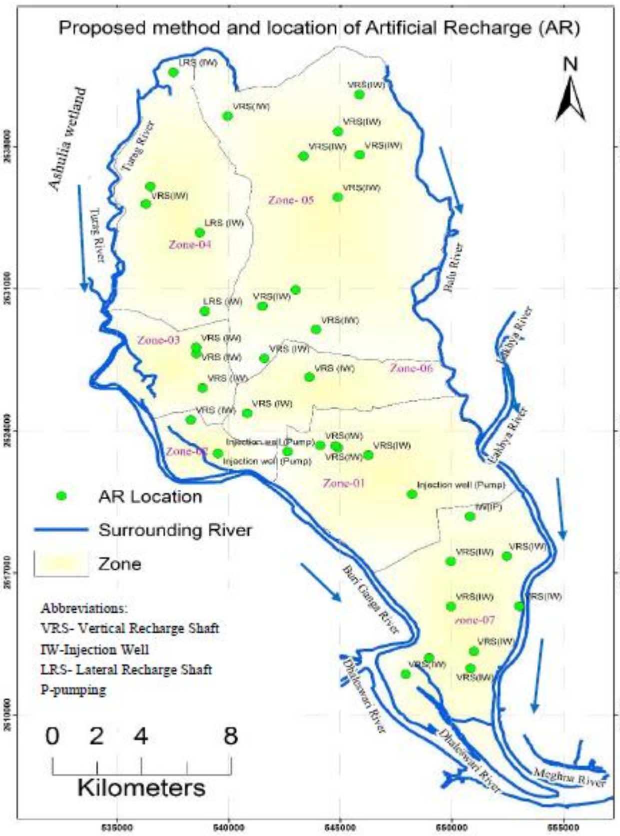


Figure 9: Proposed locations of injection wells in Dhaka for artificial recharge (AR) (Prodhania, 2016).

Appendix I: Artificial recharge wells. The scenario will be computed by including these wells in the model.

3. Results

This section will describe the results of this study. Firstly the new input data will be presented together with the effects the new data has on the model. Secondly the results of the calibration will be presented. The calibration section will also display the final results of the groundwater level according to the model. Finally the results of the scenarios will be presented.

3.1: New input data model

3.1.1: Wells

The results suggest that the industry is located mainly outside Dhaka while all domestic and commercial wells are inside the city (Figure 10). The commercial and domestic abstractions are much higher than the industrial abstractions (Table 9). The highest total abstractions will be in the southern area of Dhaka, corresponding with zone 7 and industry area 2.

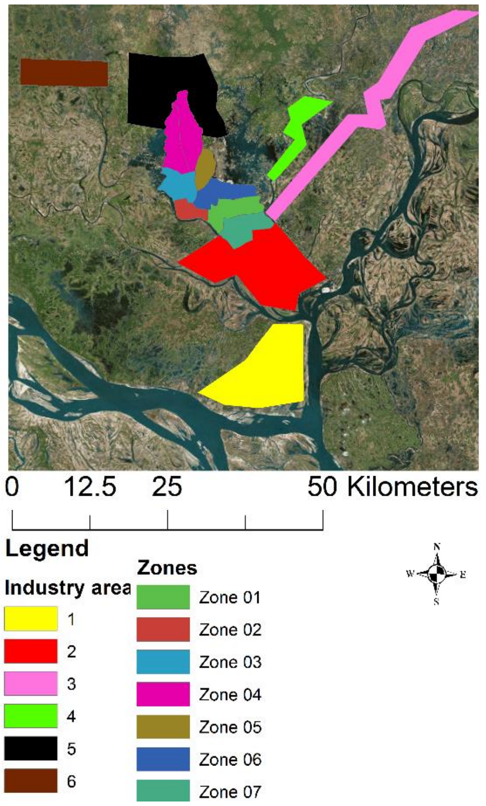


Figure 10: Overview of the areas where the PTWs are located in Dhaka

Table 9: The amount of PTWs located in the different areas in and around Dhaka (Figure 10), with the corresponding abstraction for each of the wells.

	Number of Wells	Abstraction per well (m^3/day)	Total abstraction Area (m^3/day)
Industrial wells			
Area industry			
1	28	805	22500
2	98	805	78900
3	52	805	41900
4	16	805	12900
5	103	805	82000
6	12	805	9700
Commercial and Domestic wells			
Zones			
1	144	1396	201.0
2	29	1396	40.5
3	174	1396	242.9
4	362	1396	505.4
5	322	1396	449.5
6	95	1396	132.6
7	764	1396	1066.5

3.1.2 Recharge from precipitation

The recharge from precipitation is displayed in Figure 11. The recharge in Dhaka itself is relatively low with 0.7 mm/day, while much more water percolates in the ground west of Dhaka.

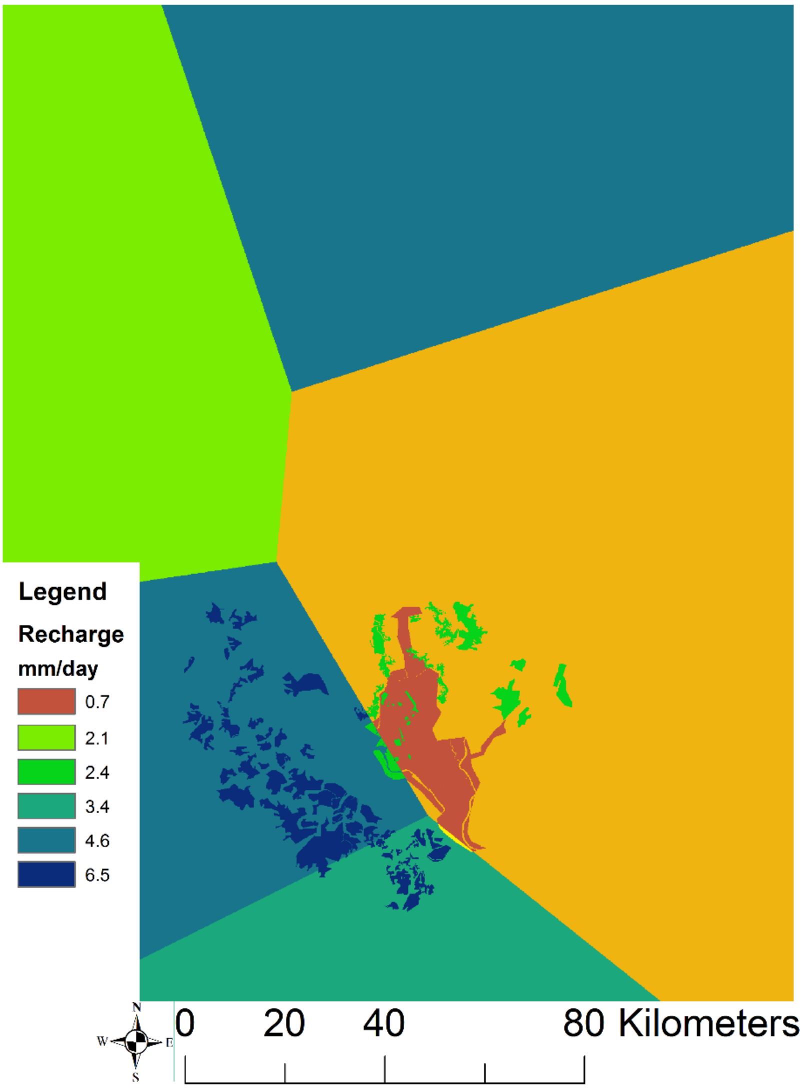


Figure 11: Recharge from precipitation over the entire model (in mm/day) based on precipitation data, potential evapotranspiration data and infiltration rates of different soil types.

3.1.3: Rivers

The rivers with the corresponding depths in and around Dhaka are illustrated in Figure 12. The depths of the rivers vary widely from -2.9 to -16 meters below surface level, but the water bodies in Dhaka are quite shallow (-2.9 to -4.0 meters).

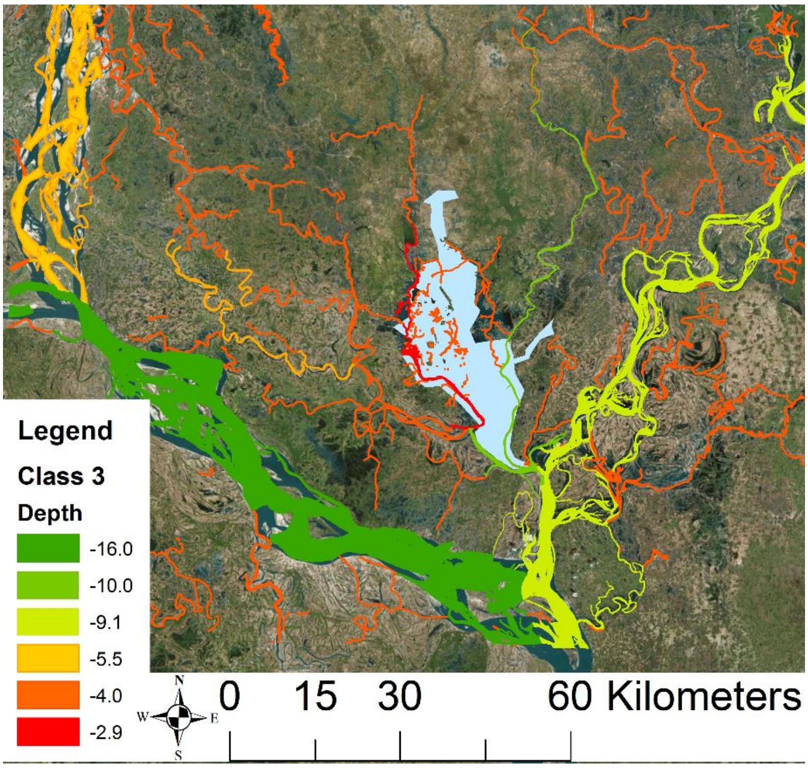


Figure 12: Rivers around Dhaka with improved depths (in meters) and the newly integrated water bodies in Dhaka (blue area)

3.1.4: Differences of heads between base model and improved model

The effects of the new input data is illustrated in Figure 13. The new PTWs data has the largest influence on the heads with differences up to 35 meter. In northern Dhaka the heads rise up to 35 meters, while the heads in southern Dhaka decrease up to 15 meter (Figure 13C). The PTWs data also cause a larger radius of the cone of depression around Dhaka, most likely caused by the industrial wells outside Dhaka.

The new river data mainly causes the heads to rise within Dhaka, most likely caused by the river bodies in Dhaka and the rivers close to the city. The heads rise up to 25 meters in the centre of Dhaka (Figure 13A).

The recharge package has a relatively small effect, causing a small rise in heads in the west and a small decrease in heads in the east. No changes larger than 5 meters are calculated (Figure 13B).

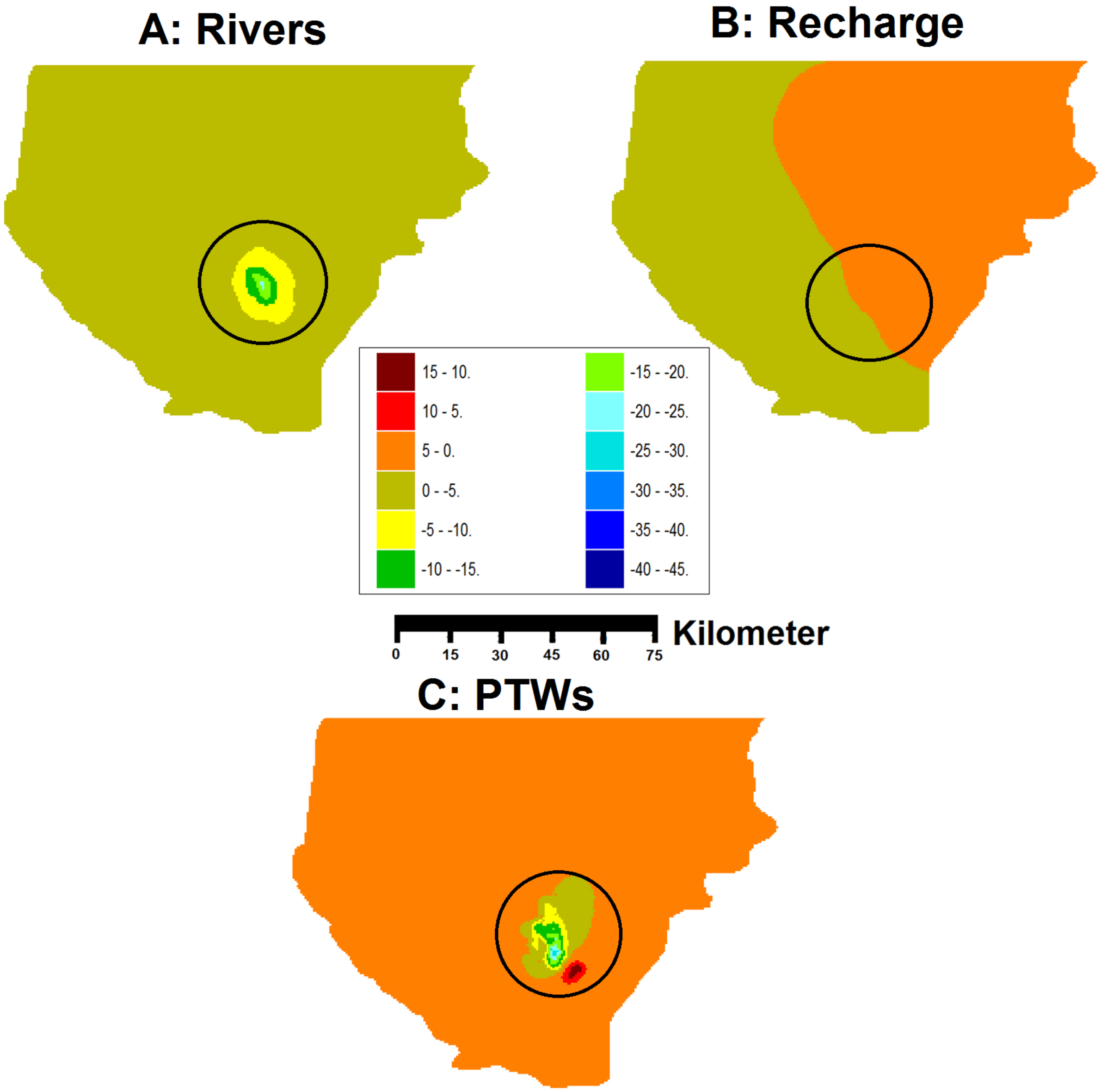


Figure 13: Difference (in meters) between base model with initial data and new input data. The heads of the base model with the river (A), recharge (B) or well PTWs (C) are subtracted from the heads of the base model. Dhaka is located in the circled area.

3.2: Results of calibration

After the input data of the model was improved, the model had was fitted to observed data. The iPEST module of iMOD fitted the computed heads to the observed data by adjusting the Kv, Kh and VA values. This section presents the optimized values (Table 10) and the resulting computed heads of the model (Figure 14). The results in Figure 14 indicate the cone of depression has a radius up to 40 km outside Dhaka. The results suggest the lowest water levels are located in the north and south of Dhaka and reach up to 80 meters below surface level.

Table 10: Representation of 3 cycles of the calibration which was computed by iMOD, showing the most essential values for the calibration and the resulting optimal value for each cycle. Starting values and optimal values of Kh and Kv are in m/day, while the starting values and optimal values of VA are dimensionless

	Type	Layer	Starting value	Minimal multiplication factor	Maximal multiplication factor	Optimal multiplication factor	Optimized value
Cycle 1							
	Kh	1	10.0000	0.25	4.50	0.59	5.8962
	Kh	2	10.0000	0.25	4.50	1.41	14.1156
	Kh	3	15.0000	0.17	3.00	0.61	9.1932
	Kh	4	17.3000	0.14	2.60	1.84	31.8754
	Kh	5	15.0000	0.17	3.00	3.00	45.0000
	Kh	6	29.0950	0.09	1.55	1.50	43.6425
	Kh	7	17.3000	0.14	2.60	0.42	7.2724
	Kh	8	17.3000	0.14	2.60	1.00	17.3000
	Kh	9	17.3000	0.14	2.60	1.00	17.3000
	Kv	1	0.0100	0.02	94.00	0.14	0.0014
	Kv	2	0.0100	0.02	94.00	0.90	0.0090
	Kv	3	0.0100	0.02	94.00	0.90	0.0090
	Kv	4	0.0100	0.02	94.00	1.59	0.0159
	Kv	5	0.0100	0.02	94.00	1.00	0.0100
Cycle 2							
	Kv	1	0.0014	0.15	686.95	0.15	0.0002
	Kv	2	0.0090	0.02	104.51	0.09	0.0008
	Kv	3	0.0090	0.02	105.00	0.15	0.0014
	Kv	4	0.0159	0.01	58.99	0.14	0.0023
	Kv	5	0.0100	0.02	94.00	2.44	0.0244
Cycle 3							
	VA	1	0.1000	0.01	100.00	0.97	0.0969
	VA	2	0.1000	0.01	100.00	1.03	0.1033
	VA	3	0.1000	0.01	100.00	2.20	0.2195
	VA	4	0.1000	0.01	100.00	23.58	2.3577
	VA	5	0.1000	0.01	100.00	7.14	0.7137
	VA	6	0.1000	0.01	100.00	25.85	2.5854
	VA	7	0.0001	0.01	100.00	62.83	0.0063
	VA	8	0.0001	0.01	100.00	8.86	0.0009
	VA	9	0.0001	0.01	100.00	0.05	0.0000

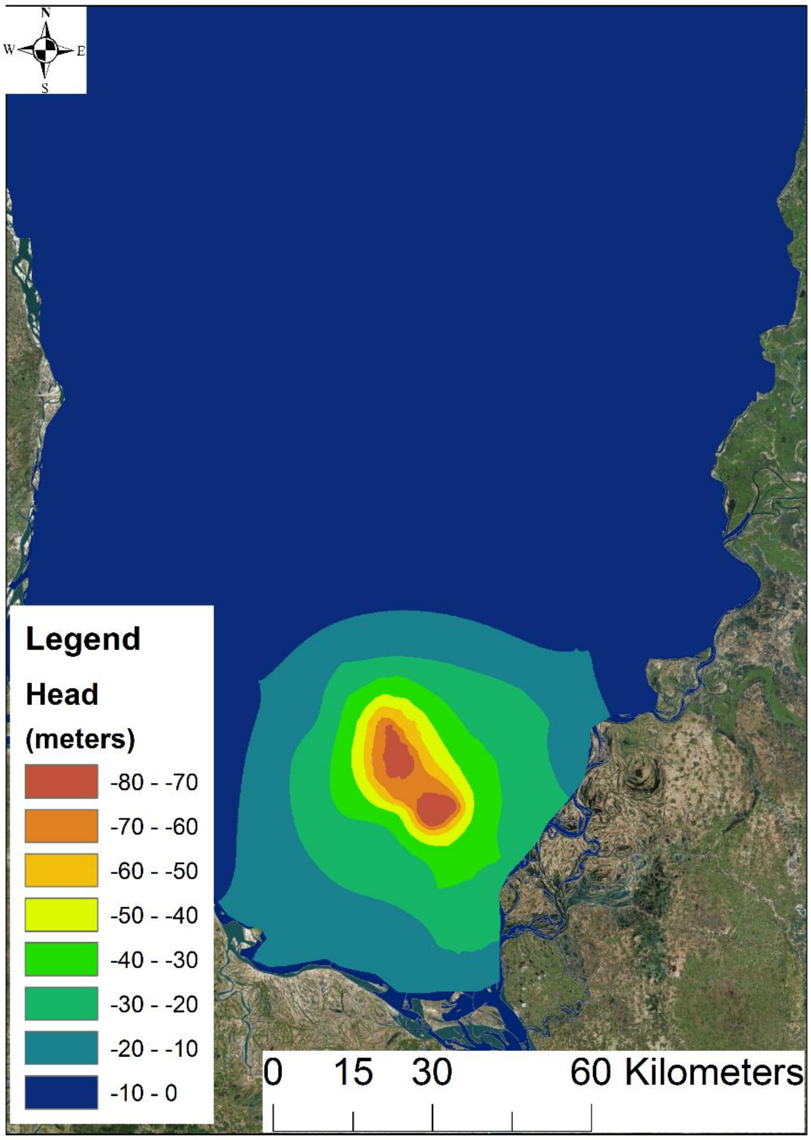


Figure 14: Heads (in meters) after all improved input data was integrated in model and all parameters were optimized in the calibration.

3.3 Results of scenarios

In this section the effects of the three scenarios will be discussed. The effects of the scenarios are visualized by subtracting the computed heads of the scenarios from the computed heads of the optimized model in Figure 14.

3.3.1: Scenario 1: DWASA master plan

If the DWASA Master plan is executed, this will have a significant effect on the groundwater level in Dhaka. The effects of scenario 1 are visualized in Figure 15. The computed heads of scenario 1 are displayed in Figure 22 in Appendix J1: *Computed heads scenario 1*. The water table can rise up to 18 meters as a result of the DWASA master plan.

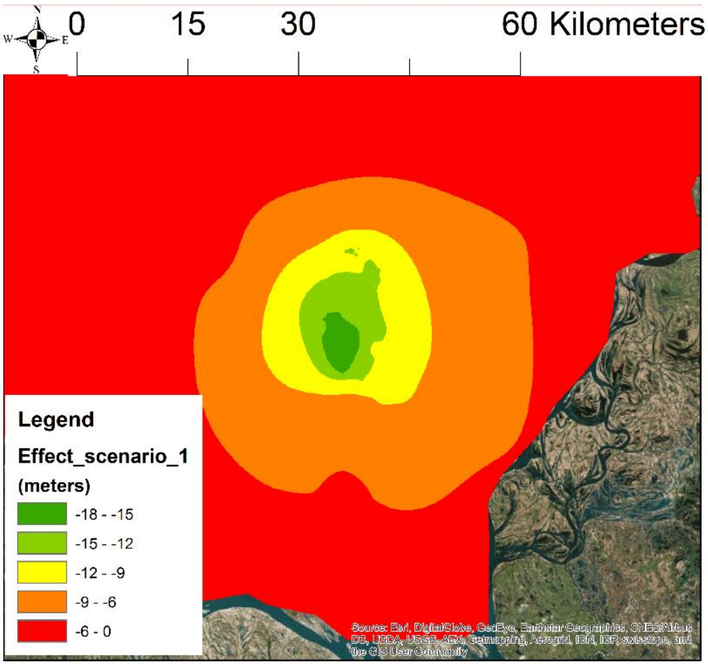


Figure 15: Effects of DWASA master plan. The map represents the difference (in meters) between the current situation according to the model and the situation if the DWASA master plan is executed.

3.3.2: Scenario 2: Industry stops abstracting water

If the industry stops abstracting water, the groundwater level can rise up to 12 meters according to the model. The effects of scenario 2 are visualized in Figure 16. The computed heads are displayed in Figure 23 in Appendix J2: *Computed heads scenario 2*. The largest effects will be in the north of Dhaka, while there are also smaller effects in the south and north-east of Dhaka.

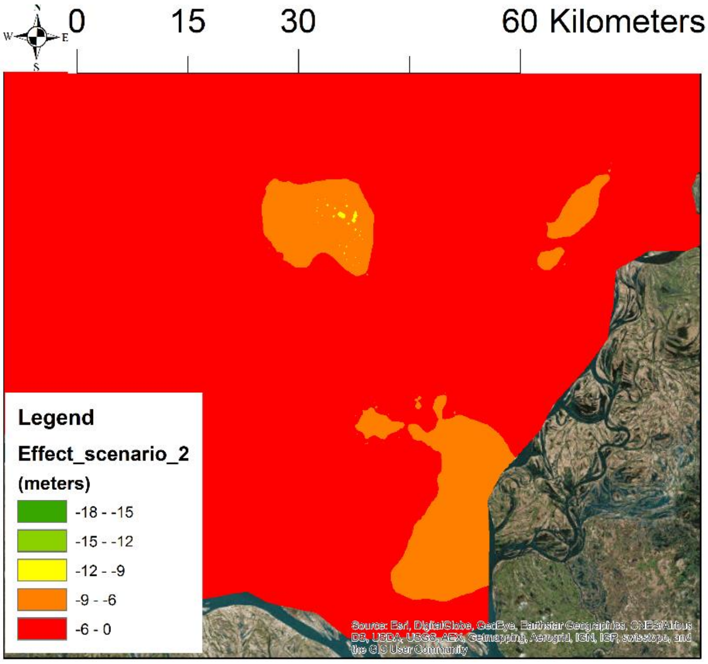


Figure 16: Effects if industry stops abstracting water. The map represents the difference (in meters) between the current situation according to the model and the situation if the industry stops abstracting water

3.3.3: Scenario 3: Artificial recharge

The artificial recharge has a large potential in Dhaka, with a possible rise of 18 meters of the water table. The effects of scenario 2 are visualized in Figure 17. The computed heads are displayed in Figure 24 in Appendix J3: *Computed heads scenario 3*. The largest effects are located in the DWASA zones, while the groundwater level just outside Dhaka will also rise up to 9 meters.

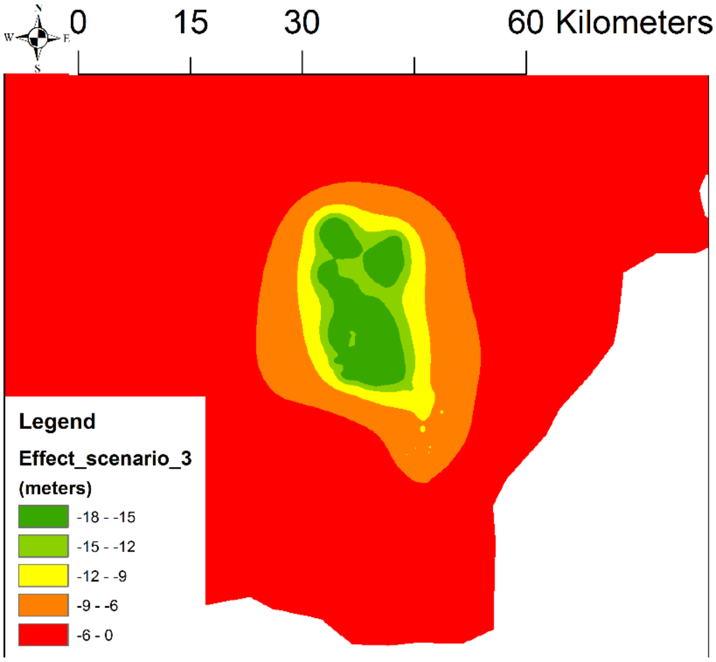


Figure 17: Effect if artificial recharge is implemented. The map represents the difference (in meters) between the current situation according to the model and the situation if the artificial recharge is implemented

4. Discussion and Conclusions

The groundwater model of Dhaka is improved and several scenarios are conducted using the model. The improvement of the model was done by adding more reliable input data to the model and fitting the model to observed data. The improved model can be used to study the effects of policies such as the implementation of an artificial recharge plan.

The results suggest the drawdown in Dhaka is up to -80 meters and this result is partially supported by previous studies. The studies conducted by IWM (2008), Hoque et al (2007) and Akther et al (2009) suggested the drawdown should be around -70 meters in 2007/2008, with an annual decrease of 2 meters, suggesting it should be around -86/-88 meters in 2016. Considering these were quite rough estimations, the result are relatively similar. The fact that the drawdown according to the model is smaller also support the suggestion by Wit (2016), who suggested the groundwater level will decrease in a slower pace towards an equilibrium.

The radius of influence is up to 40 km according to the model while IWM (2008) and Hoque et al (2007) suggested this should be only 5 km in 2008. The cone will surely have expanded since 2008, but a difference of 35 km is a very large margin, and should probably be less. The large scale of industry which evolved around Dhaka and the other private abstractions could however explain this margin, since these have a significant influence and are often neglected.

The results of the DWASA masterplan scenario also indicate that the groundwater level could recover up to 18 meters and the radius of the effects has an extent up to 25km. These results could easily be applied to calculate the effects this recovery could have on the pumping costs, since the recovery at the locations of the wells can easily be derived from the model. Therefore the financial assessment of the master plan could be elaborated and give a better indication of the financial extent of the master plan.

The results of the scenario analysis indicate that the model is a convenient tool to assess the policy scenarios of DWASA. The result of the artificial recharge suggest that the groundwater level can recover up to 18 meter while Prodhania (2016) estimated the artificial recharge would recover the aquifer up to 14 meters. The estimation of the model however gives a much clearer indication of the locations of the recovered areas than the estimations by Prodhania (2016), making it more convenient to address the effects the scenario would have on the individual wells for example.

While the application of the model as well as the primary results indicate a good representation of the groundwater level, it still upholds some uncertainties.

Firstly, the data processing of the wells was coupled with data from several years (2004, 2013, 2014 and 2015. Assuming these ratios are still the same in the current situation is not very plausible. Also the method used to quantify the amount and locations of the industrial wells, was very simplistic and sensitive for errors. However, considering all these flaws in the input data, the modelled wells still represent the current situation relatively good compared to the base model. The computed heads, resulting from the adjustments in the wells, give a much more realistic picture of the cone of depression than the base model. While the ratios and locations of the PTWs hold a lot of uncertainty, the abstraction from the DWASA wells (which forms the base for the abstractions) is a reliable and recent number.

Secondly, the recharge from precipitation is calculated using a very simplified water balance method taking only the precipitation, potential evapotranspiration and the land-use into consideration. Factors such as the surface runoff were neglected and replaced by an infiltration factor. This is an empirical factor which is not logically valid. Compared to the base model, where the recharge was not based on any observation, the input data is improved, but there is still a lot of room for fine-tuning.

Thirdly, the river depth is estimated using a single cross section for an entire river while some rivers hold a length of over 150 km, and the depth will have some very big differences over this length. The estimation of the depth gives a result which can easily vary between 2 - 5 meter. Also the river conductance was kept the same value as in the base model, while this value was very uncertain. Even though this was only a very rough estimation, the new river depths give a better estimation than the depths assumed in the base model.

Fourthly, a lot of reliability was sacrificed by inter- and extrapolating the calibration data to a single year. Both the seasonal fluctuation as well as the retained accuracy for the measurements remain questionable. Also the static water level is usually measured after a well is replaced, but the location of this well differs from the previous well, while the digitized location is not renewed. This causes an error in the location of the measurement. The data however gives a better indication of the cone of depression than other estimations in literature, because these are usually outdated and only focussed on the maximum drawdown, instead of providing a good picture of the whole region of Dhaka.

Finally, the calibration was conducted by fitting the three most sensitive parameters to the observed data, while these values do not correspond with the literature (Rijpkema, 2015). This causes the model to display a better picture of the groundwater levels, but does not necessarily mean the values are more reliable. It seems rather unlikely that the Kh is 9 m/day in the third layer, while it is 45 m/day in the fifth layer. The cause of these peculiar values is most likely the uncertainty in the layer thickness of the base model. The thickness of the layers was based on a simple interpolation between a small amount of bore logs, making it sensitive for errors. By adjusting the Kh values an error in transitivity can be straightened out.

Altogether the model is significantly improved compared to the base model, but the development of the model is far from finished. The model can be used to roughly estimate the effects of any policy scenarios, but should be further improved to give a result with the desirable accuracy.

5. Recommendations

This section will provide some recommendations about what the next steps should be in the development of the model, order to improve the model further. Firstly the possible approaches of improving the model are discussed. Secondly the recommendation about collecting, retrieving and adjusting the input data will be elaborated. Finally the author will express his final thoughst on the future development of the model.

5.1 Approaches to improve the model further

There are three different approaches recommended to improve the model: (1) Use the input data of a single year, (2) collect new data and (3) add new packages to the model. These approaches don't exclude one another and could also be executed simultaneously.

5.1.1 Collect all Input data for a single year

This study used as much of the available data as possible to improve the model. Because this data often originated from various years, this caused for some great uncertainty in the model. A good approach to improve the model therefore is to collect as much data as possible of a single year: 2013. Much of the data was already used from 2013, making it a convenient year to work from. Wit (2016) suggested the water supply system is close to an equilibrium and the groundwater level will therefore only adjust if the abstractions are changed. If the model is sufficiently accurate for 2013, only the abstractions have to be changed to make it reliable for i.e. 2017.

5.1.2 Collect new input data

While it is more convenient to collect available data, the most solid and reliable way to improve the model is to collect new data. Much of the data in the current model is simplified or generalized, causing a lot of uncertainty. DWASA possesses the necessary resources, staff and time, to collect the data necessary to create a very solid model.

5.1.3 Add new packages to the model

The packages of the model discussed in this study are the most essential packages for a steady state model, but this can be extended. There are many packages available for iMOD such as a transmissivity package, evapotranspiration etc. It could also be considered to convert the model to a transient model.

5.2 Recommendations for data

Most of the data requirements for the 3 approaches are similar. This section will not elaborate the specific data requirements for each approach separately, but will rather elucidate some convenient approaches to obtain better data. This data could be suitable for a specific approach, or for several approaches simultaneously, this will however not be further discussed for each discussed data set.

Wells

The locations of the private wells are only roughly estimated using relatively old data. There is a document available at DWASA where the exact locations of the private wells are described. Also the type of private well (industrial, commercial etc.) is described. This should be digitized and integrated into the model.

The abstractions of the private wells are based on relatively old data and should be updated. Since DWASA has placed meters on several wells, DWASA should be able to obtain these abstractions. If just a few PTWs are metered, the abstractions could be specified in several categories such as hotels, apartments, garment factories etc., which could then be further generalized for the model.

The abstraction of the DWASA wells is based on the annual report of 2013, but as soon as the report of 2014, 2015 or 2016 is finished this can be updated.

There are only 546 DWASA wells in the model while this should be around 740. Besides this, a field procedure pointed out the actual location of the wells deviates up to 500 meter from their current digitized locations. The DWASA wells should be mapped correctly and integrated into the model. This data has to be obtained by measuring the coordinates of each well in a field procedure.

Calibration data

Reliable calibration data is essential for a good model. As long as a steady state model is apprehended, the data should be from the same year, season and location and should be evenly distributed over Dhaka. A field procedure should be conducted by DWASA measuring the static water level in several wells under the described conditions.

Rivers

The depth of the rivers was estimated very simplistic with some cross sections of the rivers. More data about the river depths should be collected and used to estimate the depth. A river with a length of for example 150 km should not have a constant depth, but this should vary based on measurements on the corresponding locations. The classes of the rivers (1, 2 and 3) are also simplistic and not sufficiently substantiated with literature or research. The river conductance will vary much more in reality and just alike the river depth, a single river should be divided in more classes based on reliable measurements.

Lithology

The lower layers of the model are based on a single bore log which make the data very unreliable. Assuming the data was registered correctly for this single bore log, there is no guaranty the ground formations will be uniform at this depth. A good start to improve the lithology, would be a cooperation with the gas abstraction company, who drill much deeper than water supply authorities. While gas companies don’t document the lithology of their bore logs yet, future drillings could be used observe the lithology of the deeper aquifers, to get a better understanding of the deeper aquifers.

Precipitation recharge

The precipitation recharge is estimated too simplistic. A detailed study about the actual evapotranspiration around the study area should be performed. Also more matching data should be collected, meaning the data necessary to calculate the actual evapotranspiration should descend from the same years as the precipitation. The precipitation data in this study originated from precipitation stations in 2015, but it’s very likely these stations have also collected more recent data, or old data of i.e. 2013.

There were only 3 different classes of soil (urban, sub-urban and agriculture) distinguished, while much more detailed classes could be derived from the satellite images. Also the infiltration ratios for these classes are roughly estimated by comparing them to other infiltration rates. A more detailed study should be conducted about the effects of the soil-type on the recharge in the study area.

Boundaries

The model boundaries are chosen in such a way, they won’t influence the area of Dhaka. However the detail boundary is very small and can be widened. There is data available of several bore logs outside Dhaka making it convenient to start off with mapping the lithology more accurately. Further it’s possible to map the spatial lay-out of the model outside the detail area using the same method as applied for the detail area in this study.

Transient modelling

The use of a steady state model limits the application of the model to some extent. The model is conducted using average data (average precipitation, average abstraction) etc. and therefore only computes an average head for a year. The head will however fluctuate a lot during a year, depended on the dry- and rain seasons. This means the model can also only compute the average head for a scenario and not the actual head on any given moment. If the model is desired to be used to estimate the amount time for a policy change to take effect or to analyse seasonal effects, it should be transferred to a transient model. To realize all the data which will vary over the years (abstractions of wells, location of wells, precipitation etc.) has to be collected for several years.

5.3 Final thoughts of the author

Improving a model can be an endless cycle of data collection, calibration and application. Under data-scarce conditions Hogeboom et al (2015) advised to prevent overly sophisticated modelling while at the same time building upon available data and literature. A model shouldn't be considered a copy-, but merely as a mirror of reality, and the Dhaka model can still be considered as a very dusty mirror. The next modeller working on this model should therefore not feel challenged to describe every little detail about Dhaka in the model, but should simply attempt to wipe the dust of this mirror of Dhaka as much as possible.

References

Ahmed, Z. (2006). *A Study on Groundwater Deletion and Land Subsidence in Dhaka City.* Dhaka: Department of Water Resources Engineering, Bangladesh University of Engineering and Technology.

Akther, H., Ahmed, M., & Rasheed, K. (2009). *Spatial and Temporal Analysis of Groundwater Level Fluctuation in Dhaka City, Bangladesh.* Dhaka: Asian Journal of Earth Sciences.

Andren, A. W. (2014). *Groundwater Drawdown.* Wisconsin: University of Wisconsin System.

Bangladesh Meterological Department (BMD). (2013). *Evapotransipration data provided by BMD.* Dhaka.

Bangladesh Meterological Department (BMD). (2015). *Precipitation data provided by BMD.*

Bangladesh Water Development Board (BWDB). (2009). *Cross sections rivers provided by BWDB.*

Bangladesh water development board (BWDB). (2014). *List of Observation Wells, Automatic Water Level Recorder and Ground Water Sampling Stations.* Dhaka: Ground Water Hydrology Sub-Division.

Bates, R., & Jackson, J. (1984). *Dictionary of geologic.* New York: American Geological Institute: Garden City.

Burgess, W. G., Hasana, M. K., Rihania, E., Ahmedb, K. M., & Darlinge, M. A. (2011). *Groundwater quality trends in the Dupi Tila aquifer of Dhaka, Bangladesh: sources of contamination evaluated using modelling and environmental isotopes.* London: Taylor & Francis.

CUS. (2010). *City Cluster Economic Development: Bangladesh Case Study.* Dhaka: Centre for Urban Studies.

Doherty, J. E., & Hunt, R. J. (2010). *Approaches to Highly Parameterized Inversion: A Guide to Using PEST for Groundwater-Model Calibration.* U.S. Geological Survey Scientific Investigations.

Driscoll, F. G. (2012). *Groundwater and Wells (second edition).* St. Paul, Minnesota: Johnson Division.

DWASA. (2013). *Annual Report 2012-2013.* Dhaka.

DWASA. (2014). *Water Supply Master Plan for Dhaka City.* Dhaka.

DWASA. (2015). *Consumer Information.* Dhaka: DWASA.

Esri, GeoEye, Geographics, E., DS, C., USDA, USGS, . . . Community, G. U. (2016). *BAsemap World Imagery.* ArcMap.

FAO. (2014). *Bangladesh*. Retrieved June 1, 2016, from AQUASTAT: http://www.fao.org/nr/water/aquastat/countries_regions/BGD/index.stm

Fetter, C. W. (2001). *Applied Hydrolgeology* (fourth ed.). Wisconsin: University of Winsconsin - Oshkosh.

FracFocus. (2016). *Fluid Flow in the Subsurface*. Retrieved June 1, 2016, from FracFocus: https://fracfocus.org/groundwater-protection/fluid-flow-subsurface-darcys-law

Freeze, R., & Cherry, J. (1979). *Groundwater, 1st edn.* Englewood Cliffs: Prentice-Hall, Inc.

Gavin, H. P. (2016). *The Levenberg-Marquardt method for nonlinear least squares curve-fitting problems 2016.* Duke: Department of Civil and Environmental Engineering; Duke University.

Hedrick, S. (2016). *WATER IN CRISIS - SPOTLIGHT ON BANGLADESH*. Retrieved June 1, 2016, from The Water Project: https://thewaterproject.org/water-crisis/water-in-crisis-bangladesh

Hiscock, K. M., & Bense, V. F. (2014). *Hydrogeology Principles and Practice (Second Edition).* Wiley Blackwell.

Hogeboom, H.J., Oel, R. v., Krol, M., & Booij, M. (2015). *Modelling the Influence of Groundwater Abstractions on the Water Level of Lake Naivasha, Kenya Under Data-Scare Conditions.* Springerlink.com.

Holierhoek, E. (2016). *Pump Design, Selection and Operation.* Dhaka: Vitens Evides International.

Hoque, M. A., Hoque, M. M., & Ahmed, K. M. (2007). *Declining groundwater level and aquifer dewatering in Dhaka metropolitan area, Bangladesh: cause and quantification.* Dhaka: Hydrogeological Journal.

Hushey, W., & Crawford, P. (1967). *Performance of petroleum reservoirs containing vertical fractures in the matrix.* Society of Petroleum Engineers Journal.

infoplease. (2016). *infoplease.com*. Retrieved June 23, 2016, from Population Statistics.

IWM. (2008). *RESOURCE ASSESSMENT AND MONITORING OF WATER SUPPLY SOURCES FOR DHAKA CITY.* Dhaka.

IWM. (2015). *Shapefiles of rivers in Bangladesh.*

Kabir, A., & Parolin, B. (2013). *PLANNING AND DEVELOPMENT OF DHAKA – A STORY OF 400 YEARS.* Kensington: University of New South Wales.

Knochenmus, L. A., & Robinson, J. L. (1996). *Descriptions of Anisotropy and Heterogeneity and Their Effect on Ground Water Flow and Areas of Contribution to Public Supply Wells in a Karst Carbonate Aquifer System.* Washington: United States Geological Survey Water-Supply.

Kruseman, G., & Ridder, N. d. (1991). *Analysis and Evaluation of Pumping Test Data (Second Edition).* Wageningen: International Institute for Land Reclamation and Improvement.

Kumar, C. P. (2015). *Data Requirements for Groundwater Modelling.* Roorkee: National Institute of Hydrology.

Lee, C.-H., Chen, W.-P., & Lee, R.-H. (2006). *Estimation of groundwater recharge using water balance coupled with base-flow-record estimation and stable-base-flow analysis.* Springer-Verlag.

Misstear, B. D. (2000). *Groundwater Recharge Assessment: A Key Component of River Basin Management.* Dublin: Department of Civil, Structural & Environmental Engineering, Trinity College Dublin.

Parvin, M. (2013). *Projecting the population size of Dhaka city with migration using growth rate method.* IOSR Journal of Mathematics.

Prodhania, M. Z. (2016). *Assessment of the Effectiveness of Artificial Recharge for Mitigating Groundwater Depletion in Dhaka City.* Delft: UNESCO-IHE.

Rahman, M. A., Wiegand, B. A., Badruzzaman, A. B., & Ptak, T. (2013). *Hydrogeological analysis of the upper Dupi Tila Aquifer, towards the implementation of a managed aquifer-recharge project in Dhaka City, Bangladesh.* Dhaka: Hydrogeology Journal.

Rijpkema, S. (2015). *Draft report Groundwatermodel Dhaka.* Dhaka: Vitens Evides International.

Robinson, S. (2004). *Simulation: The practice of Model Development and Use.* West Sussex: John Wiley & Sons, Ltd.

Sankovski, A., Barbour, W., & Peppe, W. (2000). *Quantification of the IS99 emission scenario storylines using the atmospheric stabilization framework (ASF).* Technological Forecasting & Social Change.

SRTM. (2015). *Shuttle Radar topography Mission*. Retrieved 2015, from http://www2.jpl.nasa.gov/srtm/

Todd, D. K., & Mays, L. W. (2005). *Groundwater Hydrology.* New York: John Wiley & Sons, Inc.

United States Geological Survey (USGS). (2016, May 2). *Groundwater quality*. Retrieved from USGS.gov: http://water.usgs.gov/edu/earthgwquality.html

Vermeulen, P., Burgering, L., & Minnema, B. (2016). *iMOD User Manual.* Delft: Deltares.

Wada, Y., van Beek, L. P., van Kempen, C. M., Reckman, J. W., Vasak, S., & Bierkens, M. F. (2010). *Global depletion of groundwater resources.* Geophysical research letters.

Wit, G. d. (2016). *Draft theme report Geohydrology.* Dhaka: Vitens Evides International.

Wit, G. d. (2016, April). Personal communication about the Geohydrology of Dhaka. (K. Hermann, Interviewer)

World Bank. (2016). *Water Supply*. Retrieved June 23, 2016, from Worldbank.org: http://www.worldbank.org/en/topic/watersupply/overview

Appendixes

Appendix A: *Glossary*

These definitions are based on the books Groundwater and Wells (Driscoll, 2012) and Analysis and Evaluation of Pumping test data (Kruseman & Ridder, 1994).

Term	**Description**
Compressibility (α, β)	The change in volume or the strain induced in an aquifer under a given stress.
Drawdown	The difference between the water table and the pumping level. This difference represents the head of water (force) that causes water to flow through an aquifer toward a well at the rate that water is being withdrawn from the well.
Hydraulic conductivity (K)	The volume of water that will move through a porous medium in a unit of time under certain circumstances.
Hydraulic resistance (c)	The resistance of an aquitard to a vertical flow.
Porosity (n)	The property of a material of containing pores or voids.
Specific Capacity	The yield per unit of drawdown of a well. Dividing the yield of a well by the drawdown, when each is measured at the same time, gives the specific capacity.
Specific Storage (Ss)	The volume of water that a unit volume of aquifer releases from storage under a unit decline in head.
Specific yield (Sy)	The volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline of the water table.
Static Water Level (SWL)	The level at which water stands in a well or unconfined aquifer when no water is being removed from the aquifer, either by pumping or free flow.
Storativity (S)	The volume of water released from storage per unit surface area of a confined aquifer per unit decline in head.
The volumetric flux (R)	The rate of volume flow across a unit area.
Transmissivity	The rate of a flow under a unit hydraulic gradient through a cross-section of unit width over the whole saturated thickness of the aquifer.

Appendix B: *Water balance*

While the individual flows are described by Darcy's law, the bigger picture is characterized in the water balance. The basic concept of the water balance is to define the volume of water during a specific time period. The difference between the total input into and total output from the volume is balanced by the change in storage in the volume (Misstear, 2000), this is described by the following equation:

$$I - O = \frac{dS}{dt}$$

Where I is the inflow, O the outflow and dS/dt the change in storage over a unit of time. The inflow and outflow can be specified and calculated with various methods. The water balance is convenient to calculate the recharge of the groundwater.

To calculate the recharge from precipitation the water balance looks as follows:

$$\frac{dS}{dt} = P - ET - q_s - q_b - q_N$$

where P is the precipitation, ET is the evapotranspiration, q_s is the surface runoff, q_b is the groundwater contribution to runoff, which is the definition of baseflow, and q_N is the net flux of any water entering or leaving the region other than precipitation (Lee et al, 2006).

Appendix C: *Modelling in iMOD*

C1: *Well package*

The well package defines the groundwater abstractions for each model layer from wells by IPF-files (iMOD Point File). The IPF-files contain the x and y coordinates of the well locations, the average abstraction rate and the model layer. The screen depth is automatically assigned to the corresponding model layer.

C2: *River package*

The river package defines the location, the water level, the bottom level, the conductance and the infiltration factor by four IDFs. The river package represents the presence of permanent water from which water may infiltrate or to which water may discharge. The source of water in the river package is unlimited which means that rivers never dry out.

The rivers package will assume there is a straight line from the top to the bottom of the river, and thus no circular cross sections are possible.

The river conductance is modelled as displayed in Figure 18. The infiltration is described by the following equations:

$$q = h * conductance$$
$$conductance = \frac{A}{c}$$

where q is the amount of water infiltrated in the ground, A is the surface area of a single cell (l*w) and c is the hydraulic resistance.

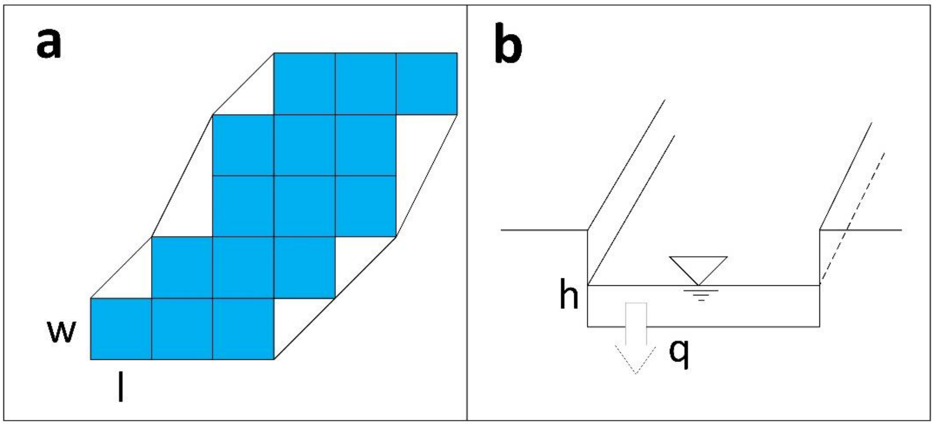


Figure 18: a: Example of how a river looks like in cell format with cells of length (l) and with (w) of the cells. b: Theoretical lay-out of the rivers with height (h) and infiltration (q)

C3: *iPEST Package*

Highly parameterized groundwater models can create calibration difficulties. Regularized inversion (combining large numbers of parameters with mathematical approaches for stable parameter estimation) is becoming a common approach to address these difficulties and enhance the transfer of information contained in field measurements to parameters used to model that system (Doherty & Hunt, 2010). In iMOD the Levenberg-Marquardt algorithm (LMA) is used for the parameter estimation. This method solves nonlinear least squares problems, which arise when fitting a parameterized function to a set of measured data points by minimizing the sum of the squares of the errors between the data points and the function (Gavin, 2016). The objective function is notated as:

$$\Phi_m(\boldsymbol{p}) = \left(\boldsymbol{y} - \emptyset(\boldsymbol{p})\right)^T \boldsymbol{Q}_1(\boldsymbol{y} - \emptyset(\boldsymbol{p}))$$

where y are the measurements with elements , $\emptyset(\boldsymbol{p})$ are the computed head for the parameters defined in p, and Q is the weight matrix assigned to the observations (Vermeulen et al, 2016). The total objective function value for the iPEST simulations performed in this thesis, also known as the Jacobian value, can be calculated as follows:

$$J = \sum_{i=1}^{n}(MSR - MDL)^2$$

where MSR is the computed value and MDL is the observed value.

For a parameter estimation in iMOD various settings have to be set. The general settings are explained in Table 11. The settings which have to be set for each parameter individually are explained in Table 14. The data is acquired by personal communication with Rijpkema and the user Manuel of iMOD (Vermeulen, 2016). Table 12 explains the settings which have to be set for each individual parameter of the iPEST simulation.

Table 11: Explanations of the general settings of an iPEST simulation

Setting	**Explanation**
Maximum number of iterations	The maximum amount of iterations the simulation should perform. An appropriate rule of thumb is to set at least as many iterations as parameters which are calibrated.
Stop criterion	Stop criterion whenever decrease of objective function J becomes less or equal to the ratio J_i/J_{i-1}. Entering a value of 0.1 means than the optimization stops whenever the objective function value J_i for the current optimization step i, is reduced less than 10% of the last objective function value J_{i-1}.
Acceptable sensitivity	The acceptable sensitivity for parameters to be included in the parameter upgrade vector, e.g. PE_SENS=0.1 mean that parameters that have less than 0.1% sensitivity will be left out until they achieve a higher sensitivity.
Number of periods	The number of periods. If PE_NPERIOD > 0, than repeat Data Set 15 for each period.
Number of batch files	Enter the number of batch files to be included during the parameter estimation. Each batch file can have its own fraction that determines the weigh for the total objective function value.
Fraction for each target	The difference in each stress period or the difference between the measurement dynamics and observational dynamics. iMODFLOW will recomputed the normalized values for the fraction. e.g. entering 1.0 and 2.0 will yield the fraction values 0.33 and 0.66, they will be summed equal to one.
Scaling option	You can choose to either use no scaling option, use scaling, use eigenvalue decomposition or use both scaling and eigenvalue decomposition.
Stopping criteria for parameter adjustment	The stopping criteria for Parameter Adjustment, e.g. PE_PADJ=0.01 means than whenever the parameter adjustment vector is less than 0.01, the optimization will stop. By default PE_PADJ=0.0 which means that the optimization will stop only whenever to parameters adjustment is applied.
Minimal acceptable absolute residual	Enter the minimal acceptable absolute residual used for the objective function. Absolute residuals smaller that PE_DRES will not be included in the objective function and therefore not influence any parameter

	adjustment. By default PE_DRES=0.0 which means that all residuals will be included.
Kriging type	Enter the type of Kriging to be used (whenever the PilotPoint concept is used). By default Simple Kriging is applied (PE_KTYPE=1), select PE_KTYPE=2 for Ordinary Kriging. The latter is used whenever a trend exists in the PilotPoints.

Table 12: Explanation of the settings which have to be set for each parameter in the iPEST simulation

Setting	
Parameter	The type of parameter which will be calibrated. The parameters possible to calibrate with the parameter estimation function are Transmissivity (KD), Vertical Permeability (KVV), Horizontal Permeability (KH), Vertical Resistance (VC), Storage Coefficient (SC), River Conductance (RC), River infiltration (RI), Drainage Conductance (DC), Anisotropy (AF), Vertical Anisotropy (VA), Horizontal Barrier Factor (HF), MetaSWAP storage coefficient (MS) and MetaSWAP conductance (MC).
Layer	The layer number of the parameter
Zone	Zone where changes in the parameter should be tested during the calibration
Initial multiplication factor	Starting multiplication factor for the calibration
Size step	Size step for the sensitivity computation.
Minimum multiplication factor	The lower boundary of the multiplication factors the parameter can reach.
Maximum multiplication factor	The upper boundary of the multiplication factors the parameter can reach.
Group number	The number of the group of the parameter. Parameter in the same group will always get the same multiplication factors.

Appendix D: *Wells*

The amount of wells was normalized according to the ratios of the industry and the surface area. This process is displayed in Table 13. Firstly the surface area is normalized to fraction 1 with the equation:

$$\frac{Surface\ Area\ i}{Total\ Surface\ area}$$

Then the normalized density is calculated with the equation:

$$\frac{Density\ i}{Total\ Density}$$

Then the amount according to the surface area is calculated with the equation:

$$Total\ Wells * Normalized\ surface\ area$$

Then the amount of wells according to density is calculated with the equation:

$$Amount\ of\ wells\ according\ to\ surface\ area * Normalized\ density$$

The final amount of wells is then calculated with the formula:

$$amount\ of\ wells\ according\ to\ density * \frac{Total\ wells}{Total\ amount\ of\ wells\ according\ to\ density}$$

Table 13: Steps of normalization

Area	Surface Area (Mm^2)	Normalized surface area	Density	Normalized Density	Amount of wells according to surface area	Amount of wells according to density	Amount of wells
1	143	0.20	1	0.0625	62	4	**32**
2	26.3	0.04	1	0.0625	12	1	**6**
3	9.0	0.01	1	0.0625	4	0	**2**
4	165.0	0.23	3	0.1875	72	14	**111**
5	131.0	0.18	3	0.1875	57	11	**88**
6	41.0	0.06	2	0.1250	18	2	**18**
7	40.3	0.06	2	0.1250	18	2	**18**
8	63.9	0.09	1	0.0625	28	2	**14**
9	59.3	0.08	1	0.0625	26	2	**13**
10	28.1	0.04	1	0.0625	12	1	**6**
Total	707	1	16	1	309	38	**309**

Total Wells	309

Appendix E: *Recharge from precipitation*

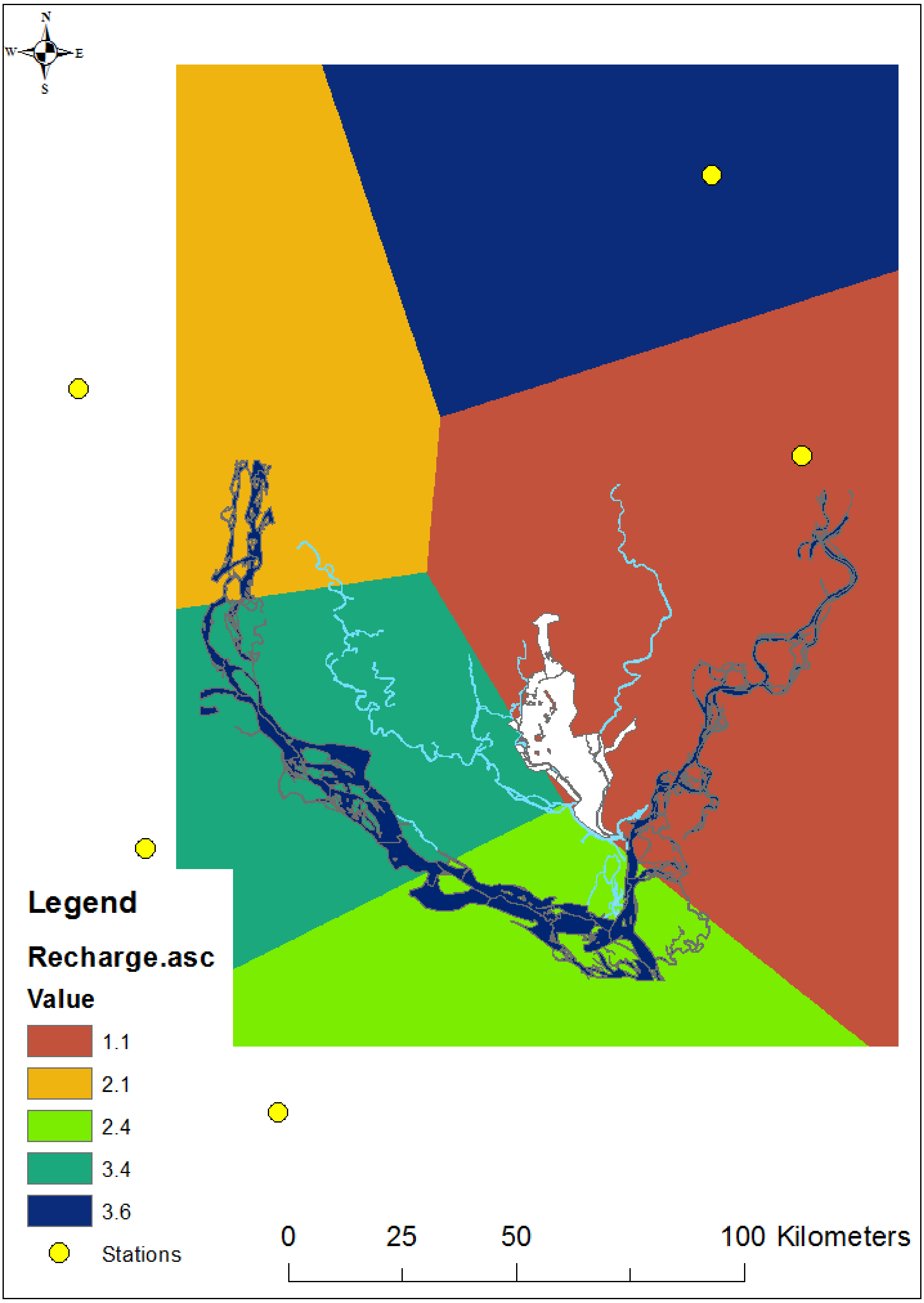


Figure 19: Interpolated Recharge from precipitation (in mm/day). Map is computed by interpolating 5 points (based on precipitation stations) around Dhaka with a nearest neighbour interpolation,

Appendix F: *Spatial layout around Dhaka*

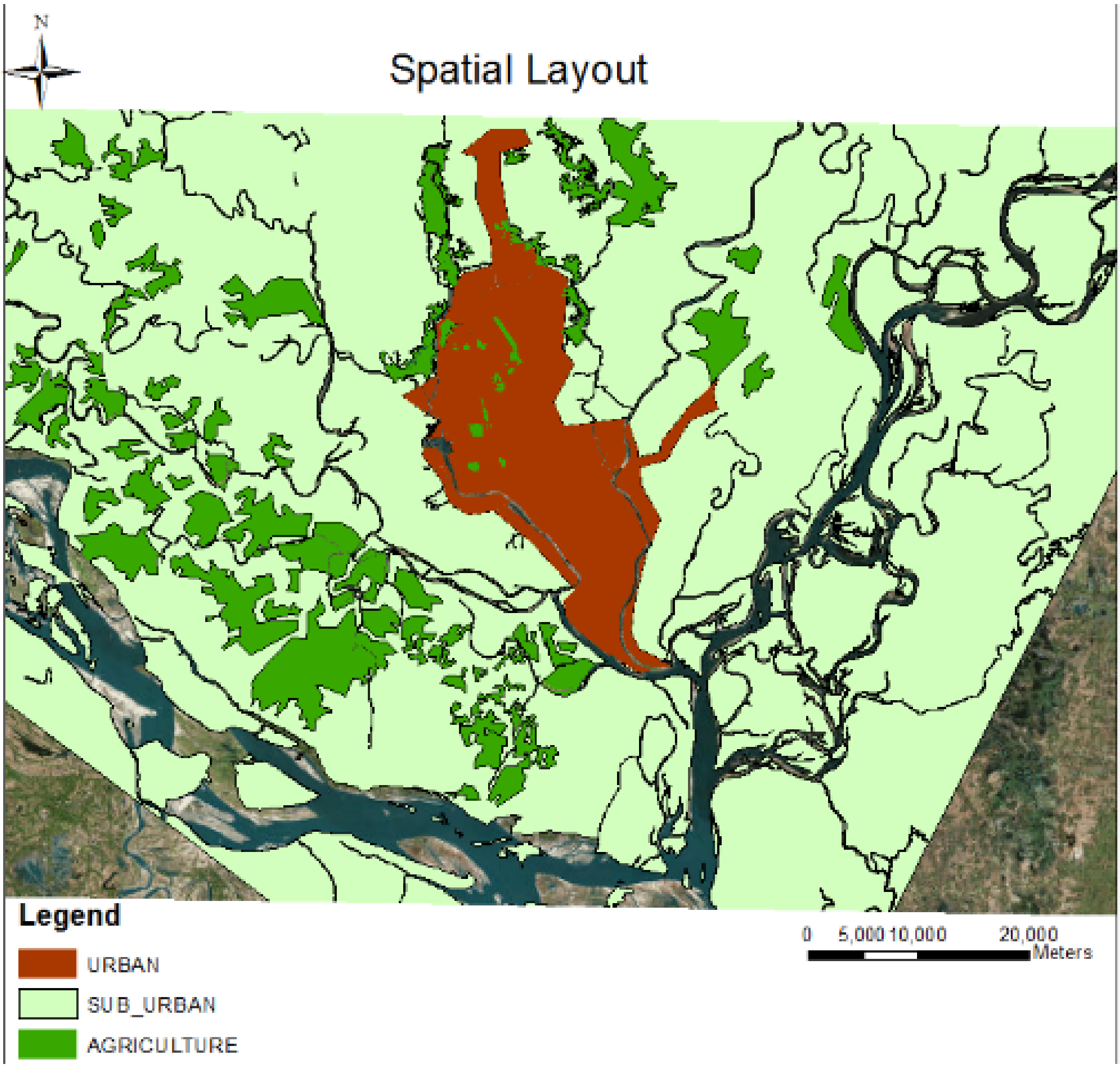
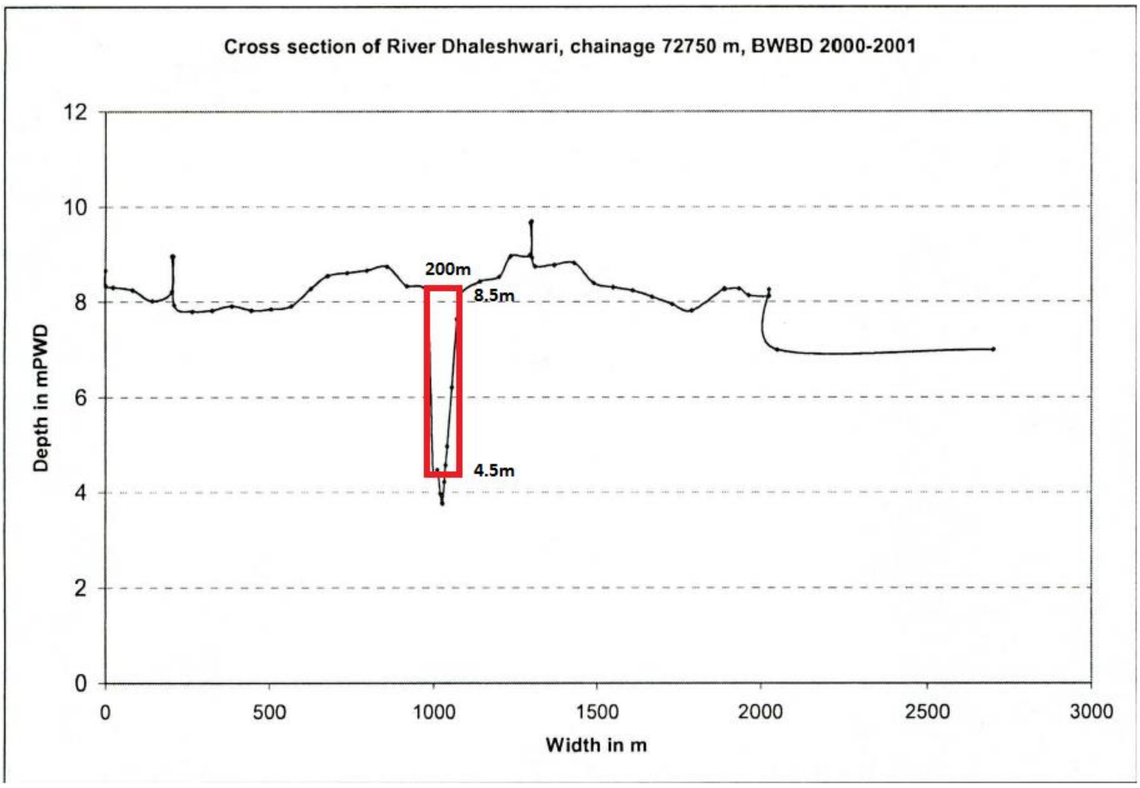
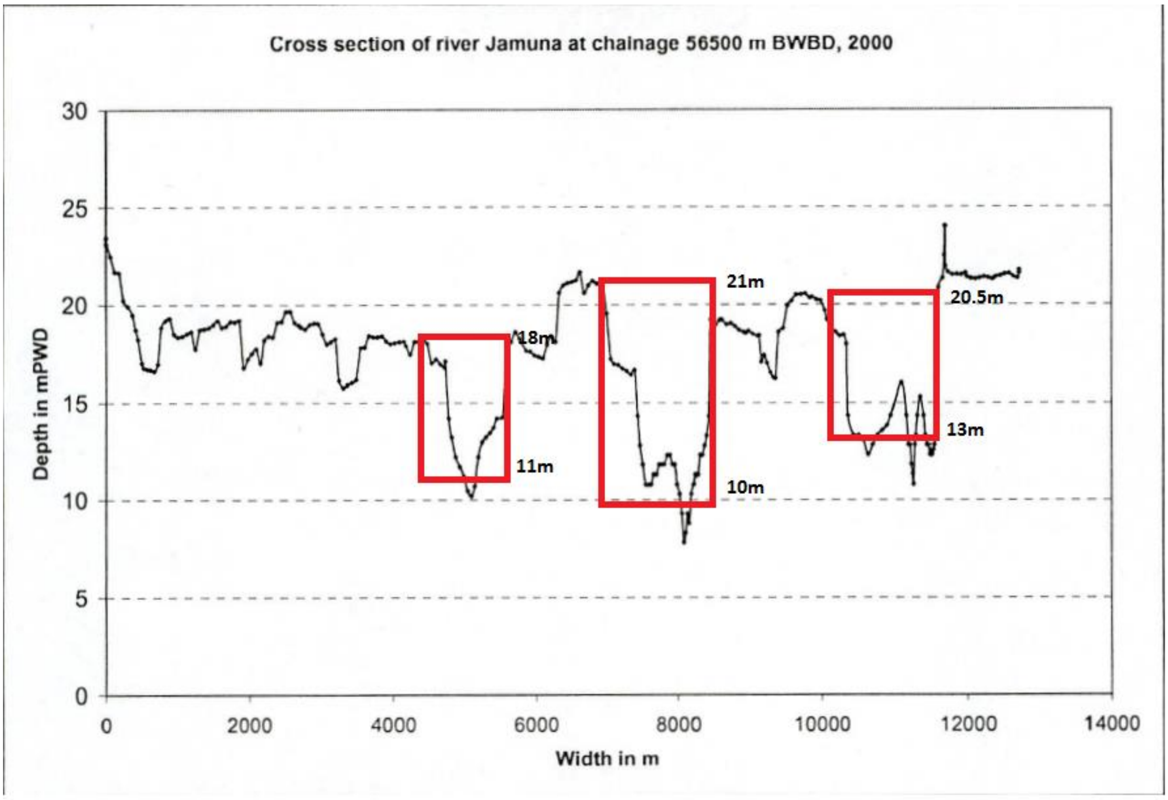


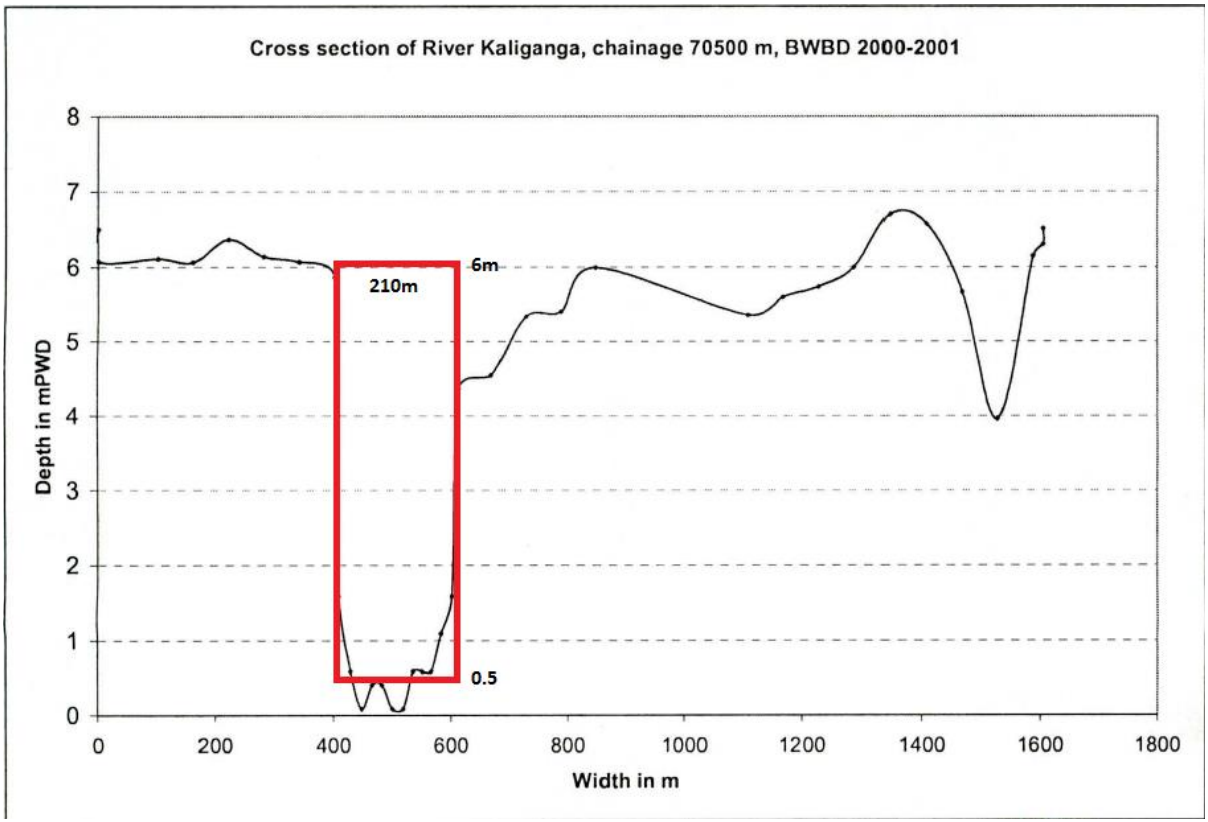
Figure 20: Spatial layout around Dhaka, distinguishing Urban, Sub-Urban and Agricultural land use within 50km of Dhaka.

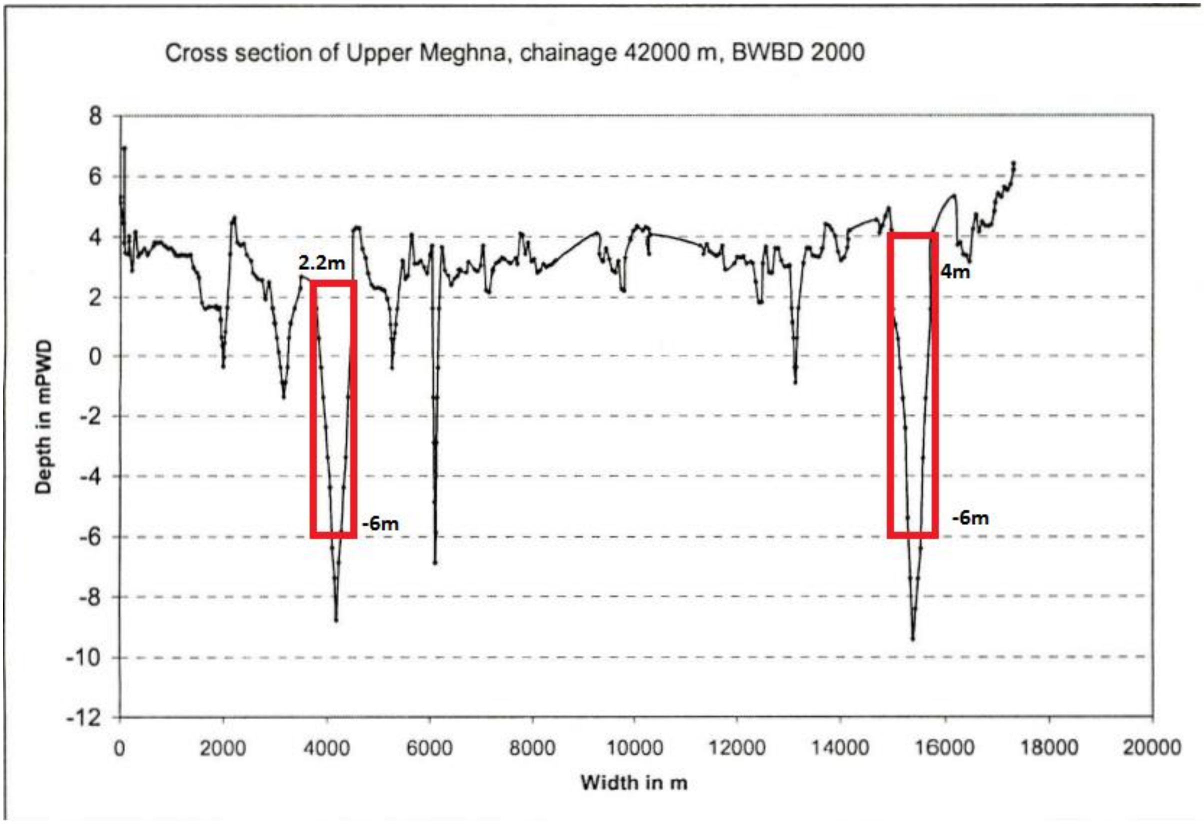
Appendix G: *Cross sections of rivers*

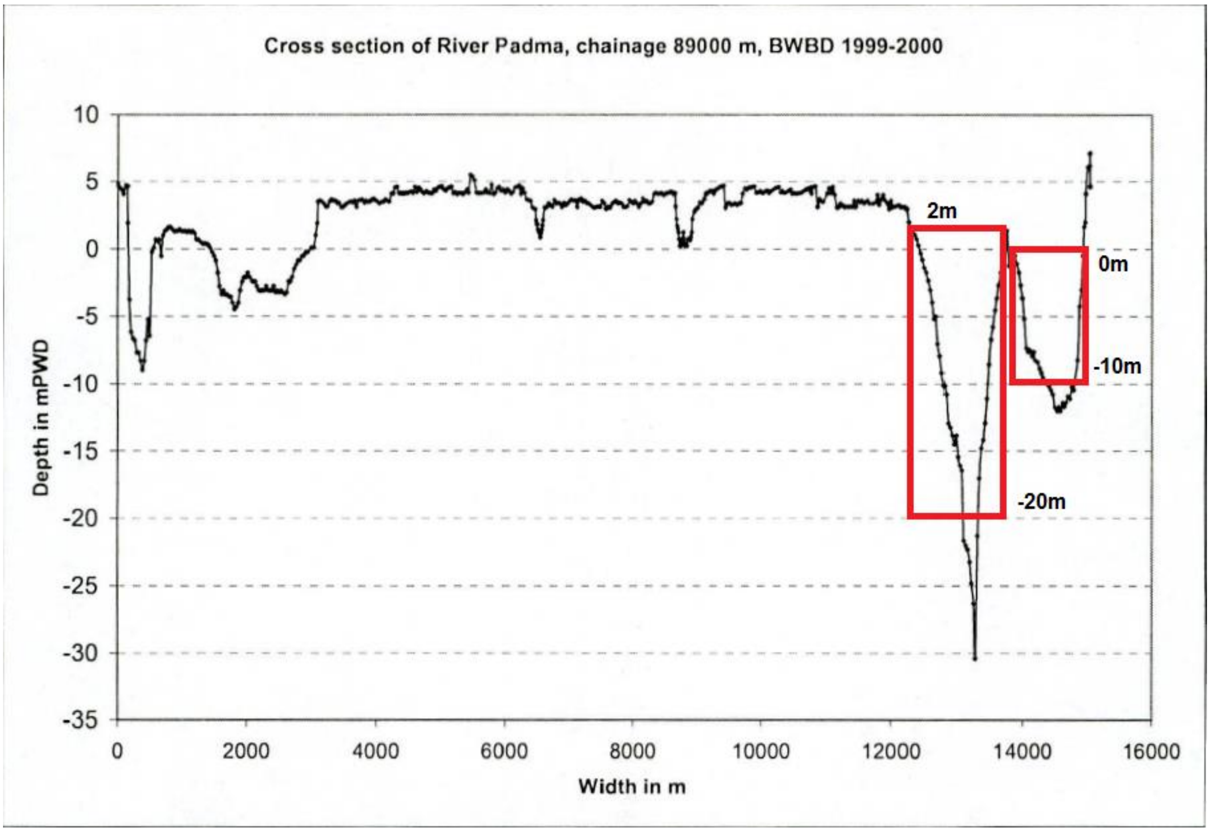
Cross sections of rivers which are within the boundaries of the model. Depths of all class 1 and class 2 rivers are based on these cross sections. Depth of rivers was estimated by drawing a rectangle around the shape of the river bed, and the height of the rectangle was assumed to be the depth of the river.

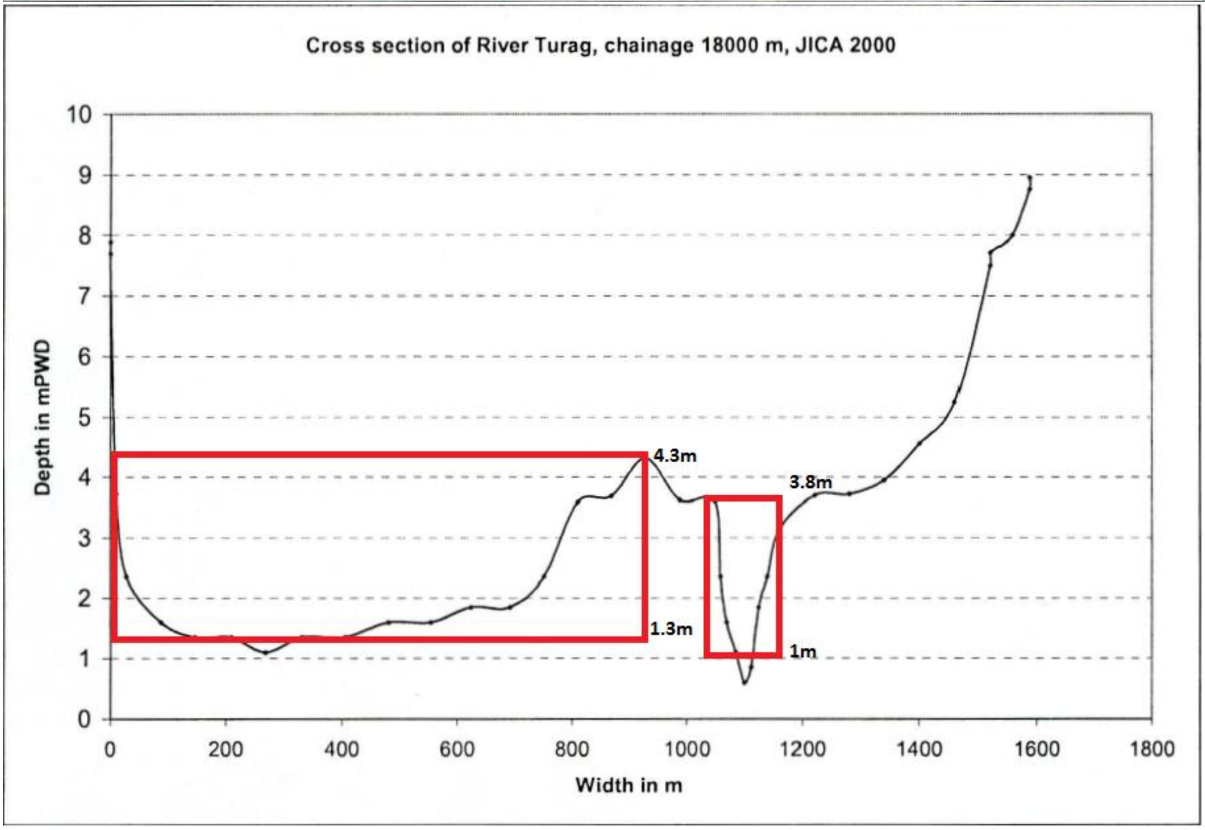





Cross section of River Kaliganga, chainage 70500 m, BWBD 2000-2001
Depth in mPWD
Width in m
0
1
2
3
4
5
6
7
8
0
200
400
600
800
1000
1200
1400
1600
1800
6m
210m
0.5


Cross section of Upper Meghna, chainage 42000 m, BWBD 2000
Depth in mPWD
Width in m
8
6
4
2
0
-2
-4
-6
-8
-10
-12
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
2.2m
-6m
4m
-6m


Cross section of River Padma, chainage 89000 m, BWBD 1999-2000
Depth in mPWD
Width in m
10
5
0
-5
-10
-15
-20
-25
-30
-35
0
2000
4000
6000
8000
10000
12000
14000
16000
2m
0m
-10m
-20m


Cross section of River Turag, chainage 18000 m, JICA 2000
Depth in mPWD
Width in m
10
9
8
7
6
5
4
3
2
1
0
0
200
400
600
800
1000
1200
1400
1600
1800
4.3m
3.8m
1.3m
1m

Appendix H: *iPEST*

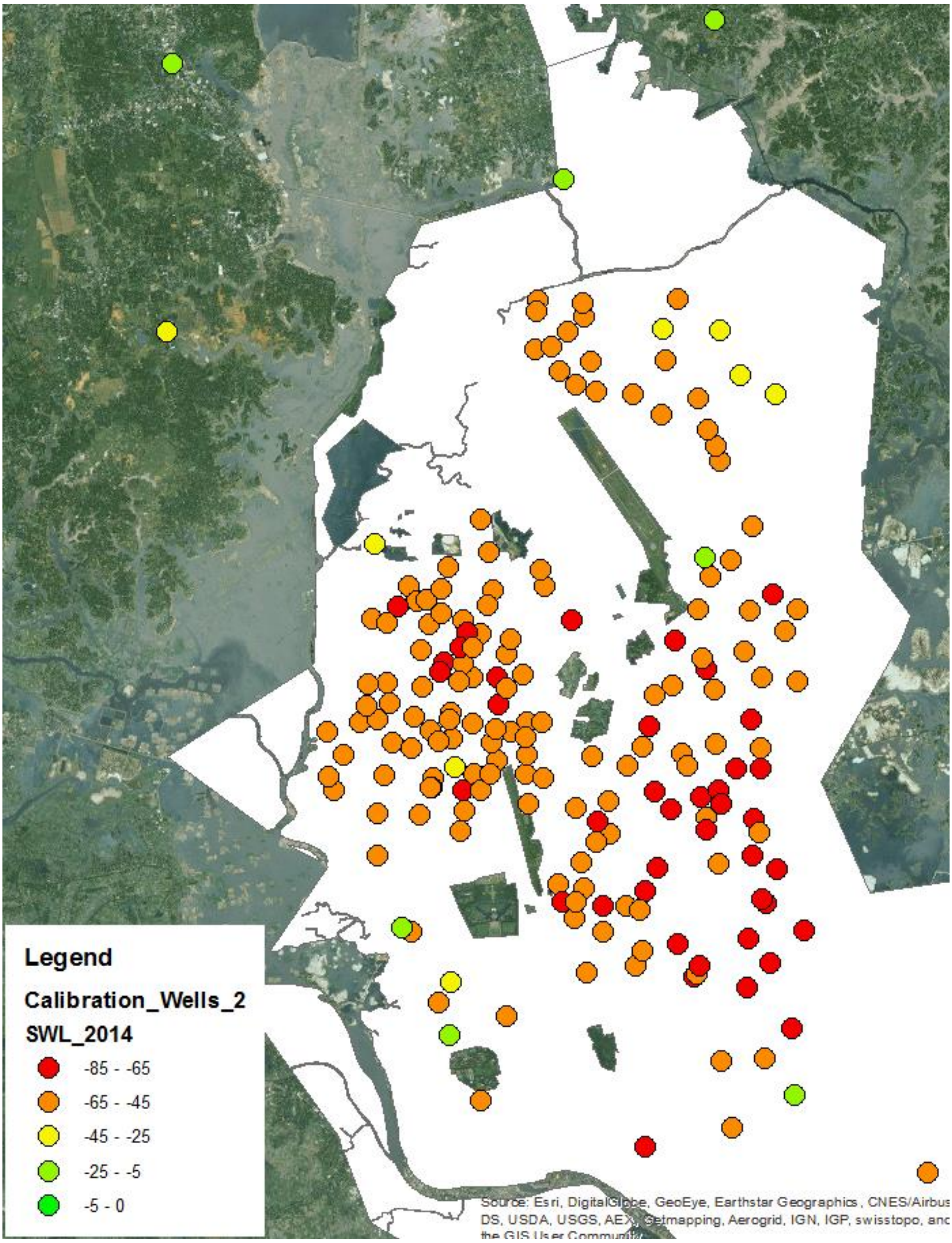
H1: *iPEST simulation: general settings*

The chosen values for the general settings of the parameter estimation are displayed in Table 14. All these values were chosen in such a way the simulation stays relatively simple and time efficient and are based on some advice of Rijpkema and Vermeulen.

Table 14: Values for general settings chosen for parameter estimation

Setting	**Value used for calibration**
Maximum number of iterations	Differs for every simulation. Approximately equal to the amount of parameters calibrated in the simulation.
Stop criterion	0.1
Acceptable sensitivity	1.0
Number of periods	0
Number of batch files	1
Fraction for each target	0
Scaling option	0
Stopping criteria for parameter adjustment	0
Minimal acceptable absolute residual	0
Kriging type	1

H2: *Locations calibration wells*



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, an the GIS User Community

Figure 21: Static Water Levels (in meters) of 211 Deep Tube Wells in Dhaka which were derived to 24th of March 24.

H3: *Parameter estimation: sensitivity analysis*

This section will explain the methodology of the sensitivity analysis and present the results. The sensitivity depends on the total objective function J which was discussed in Appendix C3: *iPEST Package*. The sensitivity is calculated with the following equation:

$$s_i = \frac{m^{-1} \sum_{j=1}^{m} J_{ij}}{\sum s_i}$$

where s_i is the sensitivity of the i^{th} parameter and is the Jacobian value for that particular observation j divided by the total observation m. The sensitivity is automatically calculated after each iteration of the parameter estimation. To obtain the sensitivity of the Kv, Kh, KVA, RI and RC a simulation was performed with the base model including the new input data. It should be noted not all packages were completely finished at the time of the sensitivity analysis.

There are two zones chosen for sensitivity analysis: A zone inside the detail area (zone 1) and a zone outside the detail area (zone 2) (not to be confused with the zones of the districts of DWASA). The values of the parameters in these zones differ significantly and thus had to be calibrated separately.

The results of the sensitivity analysis are presented in Table 15.

Table 15: Sensitivity analysis conducted by iPEST package. Fields which are coloured red are the parameters which were excluded from the calibration based on this sensitivity analysis.

Kh			**Kh**			**Kv**		
Layer	Zone	Sensitivity (%)	Layer	Zone	Sensitivity (%)	Layer	Zone	Sensitivity (%)
1	1	1.219	1	2	Error in simulation	1	1	1.587
2	1	3.895	2	2	Error in simulation	2	1	0.605
3	1	3.558	3	2	Error in simulation	3	1	0.946
4	1	2.570	4	2	Error in simulation	4	1	0.349
5	1	5.862	5	2	Error in simulation	5	1	0.161
6	1	10.390	6	2	Error in simulation			
7	1	2.684	7	2	Error in simulation			
8	1	0.060	8	2	Error in simulation			
9	1	0.007	9	2	Error in simulation			
VA			**VA**			**RC**		
Layer	Zone	Sensitivity (%)	Layer	Zone	Sensitivity (%)	Layer	Zone	Sensitivity (%)
1	1	0.000	1	2	0.001	1	-	Error in simulation
2	1	0.036	2	2	0.003	2	-	Error in simulation
3	1	0.049	3	2	0.003	**RI**		
4	1	0.019	4	2	0.001	Layer	Zone	
5	1	0.011	5	2	0.001	1	-	Error in simulation
6	1	0.017	6	2	0.000	2	-	Error in simulation
7	1	0.912	7	2	0.002			
8	1	0.006	8	2	0.000			
9	1	0.001	9	2	0.000			

H4: *Chi-square test*

	Observation 1	**Date**
Measured Value	41.61	08/02/2009
Expected value	38.58124692	
Difference	0.237766946	
	Observation 2	**Date**
Measured Value	39.3	12/11/2010
Expected value	47.10723212	
Difference	1.293917528	
	Observation 3	**Date**
Measured Value	67.53	29/06/2014
Expected value	64.7036969	
Difference	0.123454912	
	Observation 1	**Date**
Measured Value	29.41	11/08/2007
Expected value	29.32857608	
Difference	0.000226054	
	Observation 2	**Date**
Measured Value	29.41	11/08/2007
Expected value	29.32857608	
Difference	0.000226054	
	Observation 3	**Date**
Measured Value	43.37	01/02/2010
Expected value	40.76425547	
Difference	0.166565156	
	Observation 4	
Measured Value	51.52	
Expected value	50.02652396	
Difference	0.044585762	04/02/2012
	Observation 1	**Date**
Measured Value	47.71341463	21/08/2010
Expected value	39.97323506	
Difference	1.498762353	
	Observation 1	**Date**
Measured Value	48.32317073	21/01/2012
Expected value	57.68778049	
Difference	1.520181835	
	Observation 1	**Date**
Measured Value	40.24	04/04/2009
Expected value	38.58419573	
Difference	0.071057274	
	Observation 1	
Measured Value	51.37195122	
Expected value	49.94098848	

Difference	0.041001479	
Date	**Observation 2**	
Measured Value	48.47560976	
Expected value	56.05577926	
Difference	1.025032038	
	Observation 1	**Date**
Measured Value	60.06097561	20/07/2013
Expected value	57.23418655	
Difference	0.139614745	
	Observation 1	**Date**
Measured Value	54.88	29/06/2011
Expected value	46.78422481	
Difference	1.400933247	
	Observation 1	**Date**
Measured Value	52.8	21/12/2013
Expected value	56.87978831	
Difference	0.292628949	
	Observation 1	**Date**
Measured Value	62.74	18/12/2014
Expected value	62.67	
Difference	7.81873E-05	
	Observation 1	**Date**
Measured Value	63.79	17/05/2013
Expected value	63.46758673	
Difference	0.001637849	
	Observation 1	**Date**
Measured Value	51.82	21/05/2012
Expected value	52.43620736	
Difference	0.007241399	
	Observation 1	**Date**
Measured Value	57.32	16/11/2013
Expected value	61.43461564	
Difference	0.275578543	
	Observation 1	**Date**
Measured Value	53.4	19/04/2012
Expected value	50.61434023	
Difference	0.153314264	
	Observation 1	**Date**
Measured Value	47.86585366	01/06/2013
Expected value	47.85	
Difference	5.25263E-06	
	Observation 1	**Date**
Measured Value	26.29	17/12/2007
Expected value	29.4149303	

Difference	0.331980708	
	Observation 2	**Date**
Measured Value	37.96	23/03/2010
Expected value	37.63552205	
Difference	0.002797515	
	Observation 1	**Date**
Measured Value	63.36382114	22/09/2014
Expected value	64.13083333	
Difference	0.009173555	
	Observation 1	**Date**
Measured Value	60	06/07/2012
Expected value	57.51935902	
Difference	0.106982758	
	Observation 2	**Date**
Measured Value	70.12	22/10/2014
Expected value	66.02143736	
Difference	0.254435777	
	Observation 1	**Date**
Measured Value	55.79268293	23/10/2014
Expected value	54.27692884	
Difference	0.042329412	
	Observation 1	**Date**
Measured Value	50	30/06/2011
Expected value	46.10483565	
Difference	0.329082732	
	Observation 1	**Date**
Measured Value	60.13	18/07/2014
Expected value	64.73927183	
Difference	0.328168454	
	Observation 1	**Date**
Measured Value	70	29/01/2012
Expected value	61.05199667	
Difference	1.311452009	
	Observation 1	**Date**
Measured Value	48.78	26/10/2011
Expected value	46.98318364	
Difference	0.068717119	
	Observation 1	**Date**
Measured Value	40.24	27/04/2008
Expected value	66.24439809	
Difference	10.20808913	
	Observation 2	**Date**
Measured Value	40.44	03/05/2009
Expected value	66.93974672	

Difference	10.49057713	
	Observation 3	**Date**
Measured Value	42.68	26/08/2009
Expected value	67.15528605	
Difference	8.920215558	
	Observation 4	**Date**
Measured Value	41.92	11/06/2009
Expected value	67.01284267	
Difference	9.395971401	
	Observation 1	**Date**
Measured Value	55.79268293	23/10/2014
Expected value	53.5043761	
Difference	0.097867661	
	Observation 1	**Date**
Measured Value	62.5	17/11/2013
Expected value	67.11715366	
Difference	0.317625328	
	Observation 1	**Date**
Measured Value	50.3	04/04/2012
Expected value	57.36478067	
Difference	0.870065663	
	Observation 1	**Date**
Measured Value	37.27	07/03/2009
Expected value	33.71378068	
Difference	0.375119479	
	Observation 2	**Date**
Measured Value	68.44	26/04/2009
Expected value	34.3041201	
Difference	33.9684648	
	Observation 3	**Date**
Measured Value	64.02	01/08/2011
Expected value	44.0683342	
Difference	9.03299331	
	Observation 1	**Date**
Measured Value	60.36	24/02/2012
Expected value	61.0230991	
Difference	0.007205475	
	Observation 1	**Date**
Measured Value	57.24085366	26/02/2013
Expected value	54.839857	
Difference	0.10512035	
	Observation 1	**Date**
Measured Value	33.54	18/04/2007
Expected value	25.30724359	

Difference	2.67821653	
	Observation 2	**Date**
Measured Value	46.49	16/06/2009
Expected value	35.79188363	
Difference	3.197643775	
	Observation 4	**Date**
Measured Value	63.51	30/06/2014
Expected value	60.21180473	
Difference	0.180663776	
	Observation 1	**Date**
Measured Value	40.85	17/04/2010
Expected value	42.33898421	
Difference	0.052364837	
	Observation 1	**Date**
Measured Value	66.46	13/12/2014
Expected value	62.2960872	
Difference	0.27831876	
	Observation 1	**Date**
Measured Value	67.67	20/01/2013
Expected value	67.83447323	
Difference	0.000398786	
	Observation 1	**Date**
Measured Value	57.01	20/11/2014
Expected value	65.50681879	
Difference	1.102113199	
	Observation 1	**Date**
Measured Value	39.69	24/04/2008
Expected value	38.33035325	
Difference	0.048229122	
	Observation 2	**Date**
	55.72	11/12/2011
	50.22805122	
	0.600491173	
	Observation 1	**Date**
Measured Value	29.8	31/12/2007
Expected value	26.42688554	
Difference	0.430542643	
	Observation 2	**Date**
Measured Value	59.75	28/09/2014
Expected value	54.67499611	
Difference	0.471068429	
	Observation 1	**Date**
Measured Value	51.22	11/10/2011
Expected value	52.6857265	

Difference	0.040776778	
	Observation 1	**Date**
Measured Value	53.04878049	21/04/2011
Expected value	47.07688217	
Difference	0.757560142	
	Observation 1	**Date**
Measured Value	32.92	21/09/2008
Expected value	35.89720769	
Difference	0.246920755	
	Observation 3	**Date**
Measured Value	60.06097561	18/07/2013
Expected value	60.05	
Difference	2.00606E-06	
	Observation 1	**Date**
Measured Value	34.3	19/09/2008
Expected value	34.84203905	
Difference	0.008432524	
	Observation 2	**Date**
Measured Value	62.96	04/10/2014
Expected value	64.43880694	
Difference	0.033937158	
	Observation 1	**Date**
Measured Value	55.48	21/03/2013
Expected value	54.56127979	
Difference	0.015469703	
	Observation 1	**Date**
Measured Value	57.92682927	25/04/2013
Expected value	59.28228376	
Difference	0.030991668	
	Observation 1	**Date**
Measured Value	55.49	01/06/2013
Expected value	52.17001363	
Difference	0.211276723	
	Observation 1	**Date**
Measured Value	64.02	20/08/2014
Expected value	66.77009633	
Difference	0.113269716	
	Observation 1	**Date**
Measured Value	50.91	01/04/2012
Expected value	55.56858044	
Difference	0.390551127	
	Observation 1	**Date**
Measured Value	50	01/01/2011
Expected value	48.06291188	

Difference	0.078070809	
	Observation 1	**Date**
Measured Value	54.57	22/04/2013
Expected value	54.65916701	
Difference	0.000145461	
	Observation 1	**Date**
Measured Value	62.5	29/06/2014
Expected value	62.34024911	
Difference	0.000409372	
SUM CHI square	**23.23340259**	
Max value	79	
No. of measures	60	

Appendix I: *Artificial recharge wells*

Table 16: x and y coordinates of injection wells for artificial recharge according to UTM 46 coordinate system. For each well the corresponding potential artificial recharge is illustrated.

X	**Y**	**Artificial Recharge (m^3/day)**
242333	2623298	5479
233670	2625486	27397
236789	2625521	19178
237846	2629166	54795
235024	2627447	54795
233050	2628730	20548
232482	2627170	27397
235852	2630125	16438
232798	2630428	20548
232803	2630735	20548
232803	2630735	20548
233233	2632513	20000
237330	2633485	16438
238200	2631499	16438
230912	2638713	24000
230697	2637855	6000
235814	2632712	16438
233078	2636395	29863
234457	2642111	16438
232064	2644326	60000
247025	2617675	5479
242927	2615222	5479
243964	2617728	5479
244003	2619944	5479
241864	2614441	5479
244945	2615495	5479
244770	2614662	5479
246518	2620153	5479
244908	2622144	5479
239053	2625654	19178
240410	2625262	19178
238948	2625749	19178
238262	2625784	19178
239305	2638001	16438
237819	2640058	16438
240341	2640067	16438
239388	2641243	16438
240385	2643048	16438

Appendix J: *Computed heads scenarios*

Appendix J1: *Computed heads scenario 1*

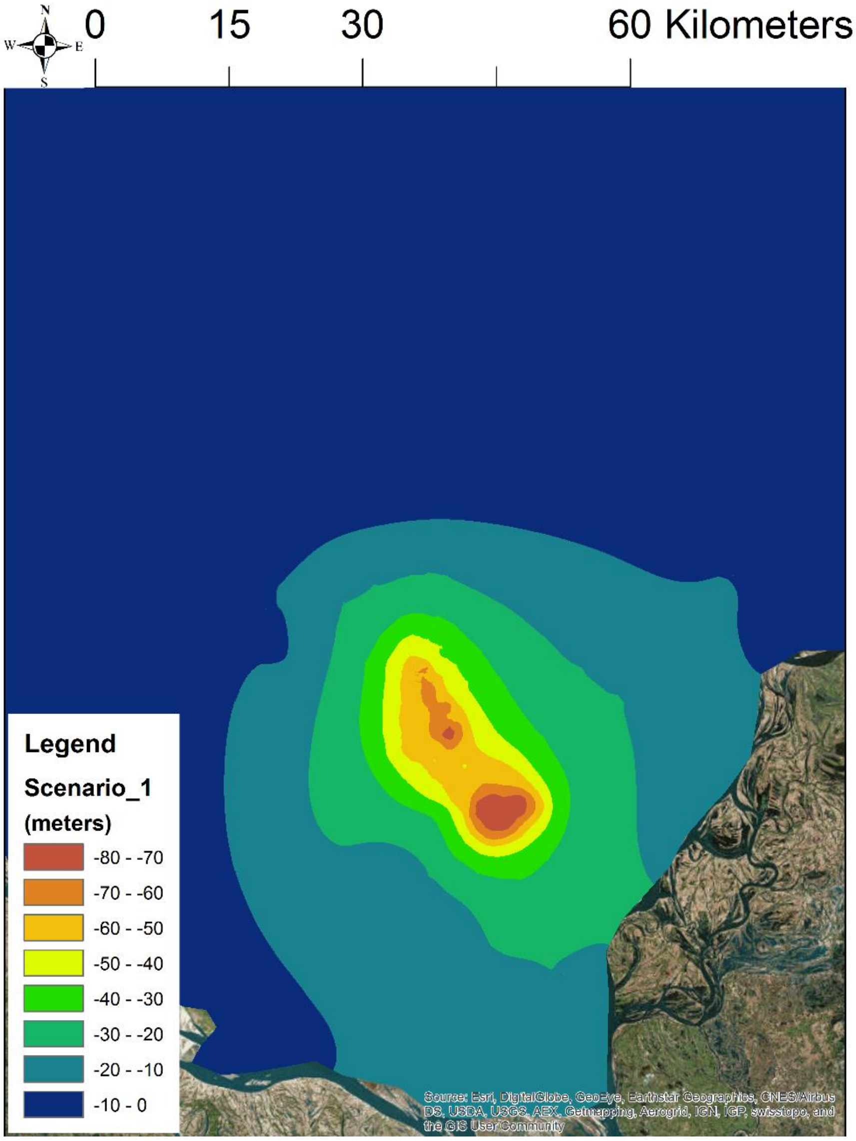


Figure 22: Resulting heads (in meters) if the master plan of DWASA (scenario 1) is executed

Appendix J2: *Computed heads scenario 2*

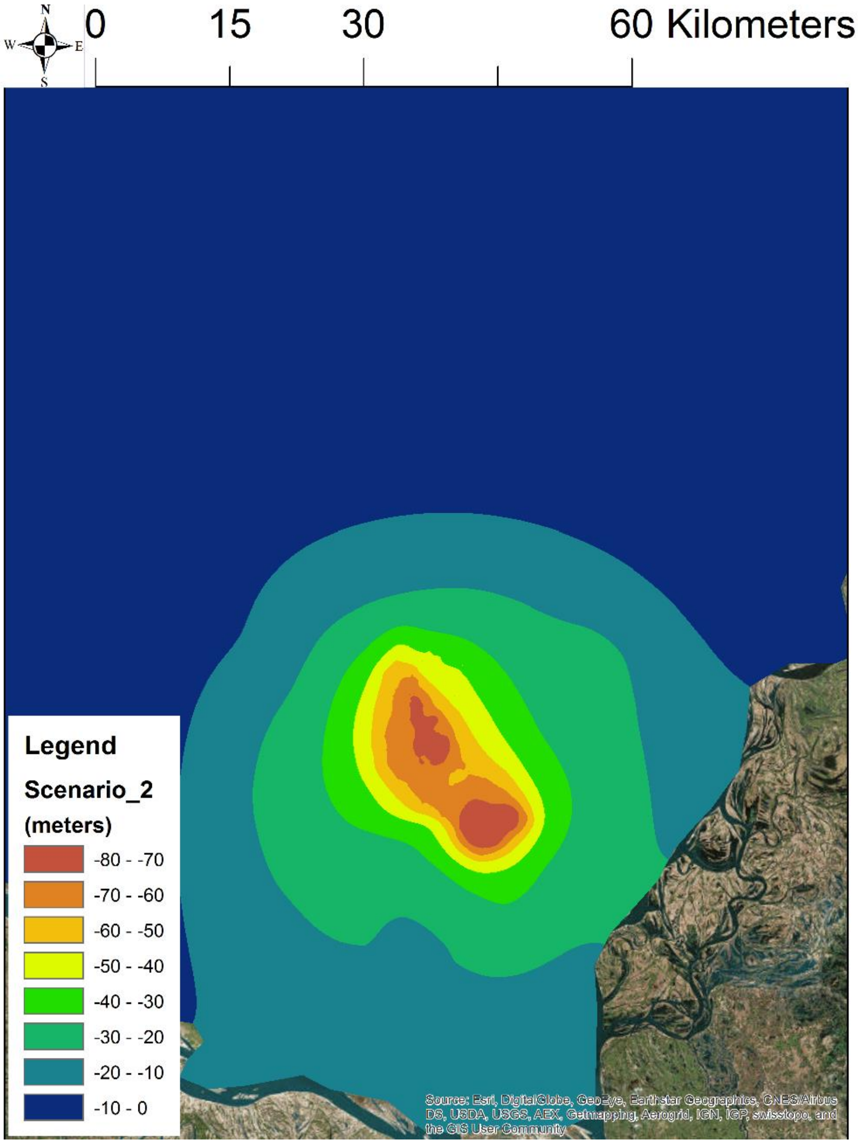
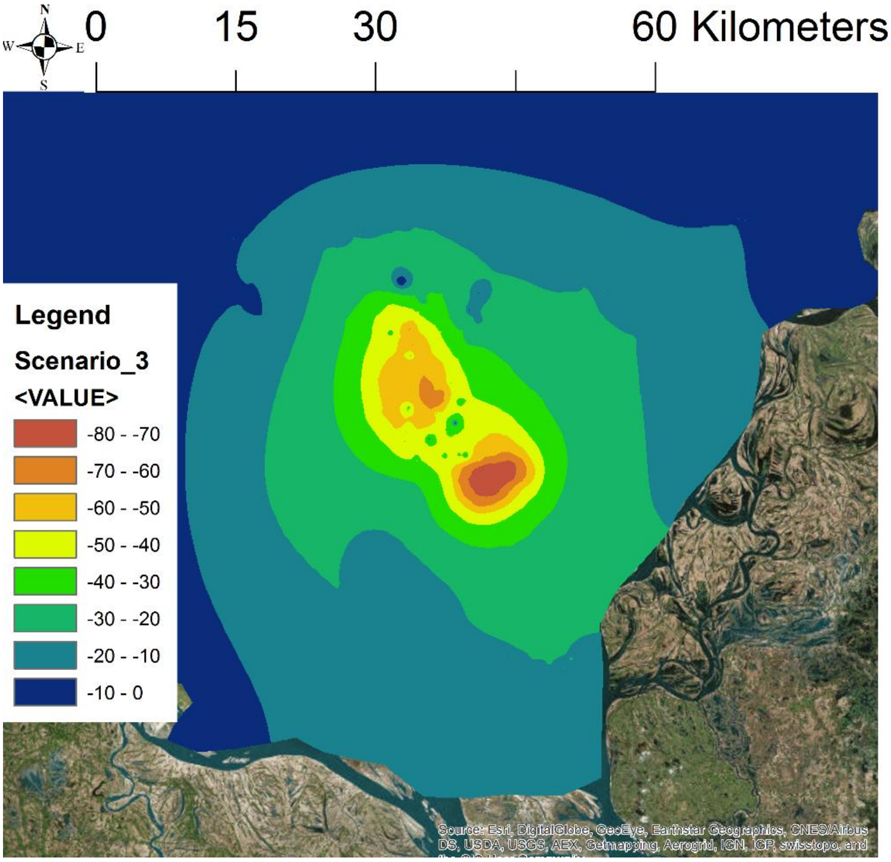


Figure 23: Resulting heads (in meters) if industry stops abstracting water (scenario 2)

Appendix J3: *Computed heads scenario 3*



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and

Figure 24: Resulting heads (in meters) if artificial recharge plan is implemented by DWASA (scenario 3)