This document is the concept report on a Bachelor Thesis.

Modelling the Jakarta groundwater system: A Sensitivity Analysis

Bachelor Thesis

Sam de Roover
S1363840

25-9-2015

Modelling the Jakarta groundwater system: A Sensitivity Analysis

Written by
Sam de Roover
s.a.w.deroover@student.utwente.nl

Supervisor Bachelor Thesis
H.J. Hogeboom, MSc
h.j.hogeboom@utwente.nl

Internship supervisor
N. Goorden
Neeltje.Goorden@deltares.nl

Picture on front page: The Pluit seawall which is reducing in height due to land subsidence. The seawall has already been overtopped multiple times by the higher than usual high tides, disrupting the lives of citizens living two meters below sea level.

Deltares
Enabling Delta Life

UNIVERSITEIT TWENTE.

Preface

The Bachelor thesis is an important part of finalising the Civil Engineering study. The only thing I was certain about was that I wanted to do my thesis abroad and to do it in the field of hydrology. Also a reason was that I wanted to conduct my thesis abroad was for the combination of my Minor study assignment. When the opportunity came for going to Indonesia I readily accepted it. The subject of land subsidence interested me since I first read about it in a magazine, so the study about Jakarta seemed interesting enough to be a part of. In this study I could be responsible for a sensitivity analysis for the groundwater system. A small part of the greater project, but I was all the more proud to contribute my part.

Although a large introduction is given into the greater study, this research is only concerned with a sensitivity analysis on the input parameters done for the current steady-state simple model of the Jakarta groundwater system.

Conducting a bachelor thesis is something not often done. It was nonetheless a pleasant experience and could not have succeeded without the help of many people. Firstly I want to thank Gilles Erkens for bringing me in contact with Deltares Indonesia, although it was a busy time for him. Secondly I want to thank Neeltje Goorden, my supervisor in Indonesia, for the personal guidance she offered with a lot of patience. Also my supervisor in the Netherlands Rick Hogeboom I want to thank for his maybe distant but direct help with questions.

After the formal thanks, I am also very grateful for my colleagues who helped me to find my way in a country with another culture and another language. Also for the support I received from home I am thankful.

Summary

Jakarta suffers from land subsidence. The rate at which this happens is alarming. The subsidence causes much direct and indirect damage to buildings and both surface and subsurface infrastructure. Also the flood risk is increased since domestic, industrial and economic buildings have a higher probability of being flooded and damages will only increase with the (economic) growth of Jakarta. Another consequence of the subsidence is the disruption of the water management, since the gradients of surface water flows change.

Groundwater abstractions play a major role in the land subsidence and it is important to schematise the Jakarta groundwater system. In this way also possible groundwater strategies, which could influence the subsidence rate, can be evaluated. Already similar models were developed, but for the current model there are now more possibilities due to technological advance and a continually growing database.

The goal of this research was to support the modelling study with an analysis of the sensitivities of the model. Although a larger database was available compared to earlier models, still a vast lack of input data is present. Data collection is the solution, but to save resources it is of importance which input data have priority in the collection. Based on the sensitivity analysis in this study suggestions could be made on where what parameters have the largest influence on the model. In this way, with the data collection one can focus on improvement of quantity and/or quality of input data for certain parameters in certain areas.

The research question which was answered in this study is to what extent the input parameters influence the model. This research question was elaborated in subquestions concerning which parameters are used in the model, what sensitivity is attributed to these parameters, and what sensitivity these parameters have in the model.

The results present the outcomes of a univariate sensitivity analysis done with a selection of parameters. This selection consisted out of the parameters for the horizontal and vertical hydraulic conductivity, the recharge of groundwater, and the groundwater abstractions. This selection was made based on found sensitivities in literature. The results of the sensitivity analysis with these four parameters are shown as differences in groundwater heads compared to the original results from the model. These results are presented in tables and maps per model layer.

The selected parameters each had their own influence on the model. Important is to notify that these influences are relative to each other and that thus on the influence of a sole parameter on the model nothing could be concluded. The horizontal hydraulic conductivity parameter had an overall influence on the model. The adjustment of the groundwater abstractions resulted in the largest sensitivities, but these were only present in the deeper layers in the northern part of the study area. Groundwater recharge also had a large overall influence on the model, but it is not certain of this statement could be made based on the found results. Changing the vertical hydraulic conductivity had the least influence when compared with the other parameters

If Deltares will continue developing the current model and sampling data for it, then therefore some recommendations are proposed in the study. It is advised to carry out a detailed research for data on abstractions in the northern, industrial districts, as in this region the model reacted most to the variations in the abstractions parameter. Also is recommended for Deltares that for the overall model more research should be into horizontal hydraulic conductivity in the whole study area, with which a more detailed, layer specific map can be made to use as input for the horizontal hydraulic conductivity parameter.

Samenvatting

Jakarta heeft last van grondverzakkingen. De snelheid met welk dit gebeurt is alarmerend. Dit leidt tot veel directe en indirecte schade aan gebouwen en (ondergrondse) infrastructuur. Ook wordt het overstromingsrisico verhoogd, sinds woningen, industriële en economische gebouwen meer kans op overstromingen hebben door hun verlaagde positie en de schade hoger wordt naarmate Jakarta (economisch) groeit. Een verwant gevolg is dat het watermanagement moeilijker wordt, doordat ook de loop van drainage en waterwegen verandert.

Grondwaterabstractie speelt een grote rol in de grondverzakkingen en het is belangrijk om het grondwatersysteem onder Jakarta te schematiseren. Op deze manier kunnen ook voorspellingen worden gedaan over mogelijke grondwatermanagementstrategieën die de grondverzakkingssnelheid kunnen beïnvloeden. Al eerder waren dit soort modellen ontwikkeld, maar voor het huidige model zijn er meer mogelijkheden door technologische vooruitgang en een groeiende database.

Het doel van dit onderzoek was om het modelleren te ondersteunen met een analyse van de gevoeligheden van het model. Hoewel er een grotere database aan data beschikbaar is vergeleken met voorgaande modellen, is er nog steeds een groot gebrek aan inputdata. Datacollectie is hier het antwoord voor, maar om middelen te sparen is het van belang te weten welke inputdata prioriteit heeft. Met de sensitiviteitsanalyse in dit onderzoek moeten suggesties worden gedaan kunnen worden in welke delen van het studiegebied welke parameters de meeste invloed hebben op het model. Zo kan er met datacollectie gefocust worden in verbetering van de kwaliteit en/of kwantiteit van inputdata voor bepaalde parameters in bepaalde gebieden.

De vraagstelling die beantwoord wordt in dit onderzoek is in welke mate de inputparameters het model beïnvloeden. Deze vraagstelling werd ondersteund met vragen over welke parameters in het model worden gebruikt, welke sensitiviteit aan deze parameters wordt toegekend in de literatuur, en welke sensitiviteit het model heeft voor de parameters.

De resultaten geven de uitkomsten van een univariate gevoeligheidsanalyse gedaan met een selectie van parameters. Deze selectie bestond uit de parameters voor de horizontale en verticale hydraulische conductiviteit, de herlading van grondwater, en de grondwaterabstracties. Deze selectie was gemaakt op basis van gevonden sensitiviteiten in literatuur. De resultaten van de gevoeligheids-analyse met deze vier parameters zijn te zien als verschillen in, vergeleken met de oorspronkelijke resultaten van het model. Deze resultaten zijn weergeven in tabellen en kaarten per modellaag.

De geselecteerde parameters hadden hun eigen effect op het model. Het is belangrijk om te zeggen dat de invloed van de parameters die is beschreven in deze studie slechts relatief aan elkander is en dat dus niks gezegd kan worden over de invloed van een parameter op het model zonder de andere in ogenschouw te nemen. De horizontale hydraulische conductiviteitsparameter had door heel het model heen invloed. De variatie grondwaterabstracties leverde de grootste gevoeligheden op, maar deze waren alleen aanwezig in het noordelijk deel van de diepere modellagen. Grondwaterherlading had ook een grote invloed door heel het model, maar het is niet zeker of dit echt gezegd kan worden op basis van de gevonden resultaten. Het veranderen van de verticale conductiviteit had de minste invloed op het model, vergeleken met de andere parameters.

In deze studie zijn recommandaties gedaan het verzamelen van data voor het model wanneer Deltares doorgaat met de ontwikkeling van het huidige model. Het wordt geadviseerd om een gedetailleerd onderzoek te doen naar de grondwaterabstracties in de noordelijk, industriële districten, sinds het model in dit gebied relatief het meest beïnvloed werd door de verandering van de abstractieparameter. Er wordt ook geadviseerd om voor het hele model onderzoek te doen naar de horizontale hydraulische conductiviteit, waarmee een meer gedetailleerdere en gelaagdere kaart gemaakt wordt die gebruikt kan worden als input voor de horizontale hydraulische conductiviteitsparameter.

Table of Contents

Appendices

1 Introduction

The capital of Indonesia, Jakarta (Figure 1), is flooded more and more regularly. This is not necessarily caused by a sea level rise or changes in river discharges, but by a drastic land subsidence. The Deltares Taskforce Subsidence (2013) stated this land subsidence is 75 to 100 mm/year. This land subsidence can be caused by natural factors, like tectonic decline and natural compaction, and human factors, like groundwater abstraction, fossil fuel mining, ground drainage and surface loading. Except an increased flood risk, also damage to buildings, foundations, and both surface and subsurface infrastructures occur due to land subsidence. Besides, it disrupts water management (Deltares - Taskforce Subsidence, 2013).

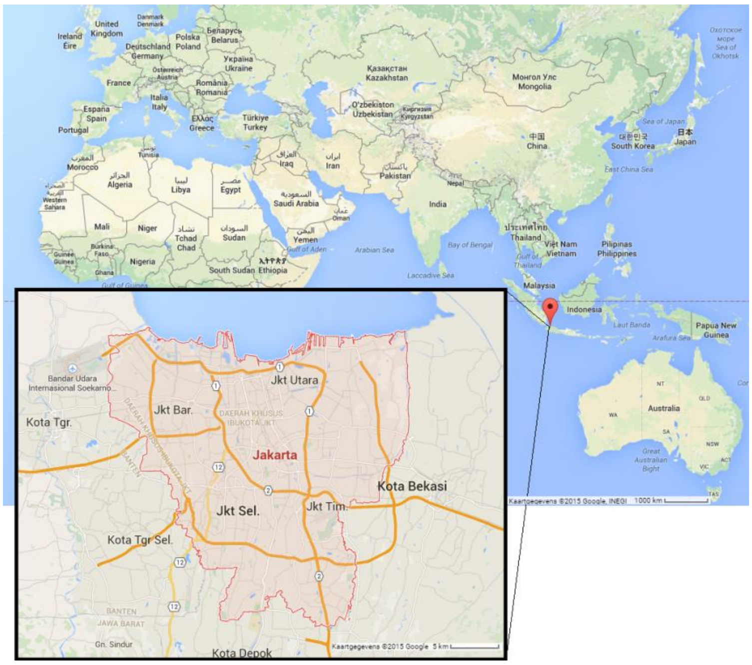


Figure 1.
Special Capital Region of Jakarta

Other large cities are also suffering from subsidence, which is believed to be caused for a major part by (over-)abstraction of groundwater. In South East Asia are other examples namely places like Tokyo, Shanghai, Bangkok, Ho Chi Minh City, Jakarta and Manila. These mega cities host millions of people and thousands of businesses and corporations. Thanks to economic development in this area, these cities keep growing, but this also means that increasing amounts of fresh water are needed. The Deltares Taskforce Subsidence reviewed some subsidence studies done in these cities. The over-extraction of groundwater was considered to be the major cause, but only in Tokyo was this confirmed, after in this city abstraction reducing policies were implemented, bringing groundwater tables up and stopping subsidence. In Bangkok also the effect of over-abstraction was acknowledged, also in the study of Yong, Turcott, and Maathuis (1995). However, Tokyo-like groundwater policies implemented in Bangkok only brought a reduced rate of subsidence, showing that subsidence there only is for a part abstraction-induced. In other cities the exact effect of groundwater abstraction on land subsidence is unknown, also because of a lack of monitoring data, and an absence of groundwater abstraction accounts.

In Jakarta, all studies which were taken in account in this report agreed on the existence of a (strong) correlation between groundwater withdrawals, and the land subsidence; it was concluded by Djaeni, Hobler, Schmidt, Soekardi, and Soefner (1986) and Soefner, Hobler, and Schmidt (1986) early on, but it is also concluded in more recent studies, among others the study carried out by the Deltares Taskforce Subsidence (2013). That groundwater abstraction and drainage are indeed major causes, but not the main causes, is argued by Chaussard, Amelung, Abidin, and Hong (2013); abstraction and drainage has a major role in local subsidence, which differentiates from the spatial land subsidence. Equal spatial land subsidence is due to natural compaction of the thick, complex Quaternary layer beneath Jakarta according to the authors. However, the most differentiated subsidence was found near locations with high groundwater withdrawal.

It is however not easy to schematise the Jakarta groundwater system as the geology is rather complex. All authors complained about the scarce available data. Some data was used for the hydrogeological models, but still the system beneath Jakarta had not been schematised in a satisfying way.

2 Research design

In this chapter the modelling goal and the goal of this research are explained, and the outline of the research is given.

2.1 Problem statement

The problem central in this project are the consequences of the land subsidence, in which groundwater abstraction plays a major role. This problem is to be solved with an adequate solution to slow down or stop groundwater abstraction-induced subsidence. For this, water management strategies have to be developed to control groundwater abstraction and, more importantly, their effects have to be evaluated to see if a strategy offers a solution to the problem. In order to do so, tools are needed that could schematise and simulate the current situation and predict the future situation with implementation of a management strategy.

Groundwater models can be such tools, which can 1) schematise the groundwater system and 2) test possible measures influencing the groundwater situation. Although previous models failed due to the uncertainties of the input data (Maathuis, Yong, Adi, & Prawiradisastra,1996) as the Jakarta basin is very complex in hydrogeological terms and as the ground layers beneath Jakarta were not properly integrally chartered, the new model can use more recent data which reduces uncertainties. Also, new modelling techniques and computer systems with a higher CPU allow the building of more complex models, which could not be built previously.

Hence, conditions are more favourable nowadays to build a proper groundwater model. Still it is not certain if this model simulates the system in a detailed way; uncertainties expressed in chapter 3.2 are nevertheless making it also now difficult to make a model trustworthy. The model must therefore not be built in its final form, but it should maintain in a form in which more data could be applied in the future. This data will originate from other studies, but also from new data collections, acquired from new boreholes. The database in which the input data is stored is to be open source, so (external) researchers could use data from the model or could store their (new) data in the database for the model.

In order for the model to make sense, uncertainties which have the most influence on the outcome, or for which the outcome is most sensitive, should be reduced first. It is likely all parameters will have an uncertainty, but by knowing what parameters in what locations have the highest sensitivity, valuable research resources can be more efficiently allocated. In this way the uncertainty reduction of the relevant parameters can be sooner achieved. As soon as a reliable groundwater model is made, a groundwater-induced land subsidence model can be made, with which measures can be evaluated to combat groundwater-induced subsidence.

The first step is, now the first version of a new model is built, to conduct a sensitivity analysis in order to establish a good basis from which the model can be supported with new data, calibrated and validated.

2.2 Research objective

The research objective is to determine which model parameters have the most impact on the outcome of the model and therefore need to be most certain. The key is also to know on what locations of the study area which parameters have what influence. To give insight in where which parameters influence the model the most, results should be published in a map of the study area.

2.3 Research questions

The research question that was answered in this report is "To which extent is the groundwater system of Jakarta, like calculated in the groundwater model, sensitive for the parameters of the groundwater model?"

Subquestions with this research question were as follows:

1 What are relevant model parameters in the iMOD model?
2 What sensitivities are given in existing models/studies for these parameters?
3 What are the sensitivities of the parameters in the model?

2.4 Scope

Since the Jakarta basin has a complex geologic system, an analytical mathematical model would not suffice, because a very concrete schematisation of the system is needed to create a model with highly detailed relations. Thus for modelling the groundwater system of Jakarta, a numerical mathematical method was used, and to be more precise, the MODFLOW Finite Difference Method (FDM), on which iMOD software is based (Vermeulen, Van der Linden, & Minnema, 2014). Other options, such as the Finite Elements Method and the Finite Volumes Method are less applicable for modelling the groundwater system of Jakarta, also because the methods may cause more complexity. The built-up of the current Deltares model is featured in section 3.3.

2.5 Methodology

The research could be divided into two tracks: a literature study in which the parameters and their possible influence on model results were researched; and a sensitivity analysis in which the model sensitivities for the input parameters were quantified.

2.5.1 Literature study

In the literature study mainly the works based around previous Jakarta groundwater models were used for evaluating the input parameters. The values used in the Deltares model were also evaluated during this review of previous studies. The results from this part of the literature study were included in section 4.1. To have a wider range than only the Jakarta groundwater studies for making an early sensitivity identification, also other models were reviewed. These may not have been useful for evaluating parameter values, but they were helpful in determining a first sensitivity qualification of the parameters. This qualification was based on how many times certain parameters were used in different models, and thus were important for modelling groundwater. With this qualification, the parameters which likely had the greatest influence on the model were selected, thus narrowing down the focus and making it possible to use research resources (mainly time) more efficient. The results are described in section **Error! Reference source not found.**.

2.5.2 Sensitivity analysis

In the study a sensitivity study was done for the influence of selected parameters relative to each other on the model results. Results were plotted in maps and graphs.

The adjustment of parameters was done by dividing and multiplying the selected parameters with two with a one-at-a-time (OAT) manner. The variance of adjustment was chosen as it was suggested by Singh (2013), and Ting, Zhou, De Vries, and Simmers (1998), in order to make the analysis not too time consuming. The sensitivity analysis was done with the OAT method, in which the parameters were adjusted one at a time, while the others parameters were not changed (Booij, 2014). The adjusted parameter however were changed for all layers it influenced at once, so a parameter was altered for all four layers, instead of one layer at a time; for layers, the change was thus coupled. This was done because for the study there was no more time to be spent. In the end four parameters were tested. With two adjustments per parameter a total of eight model runs were done, in which the reference run was excluded.

The influence of the parameters was shown by the difference in water head the parameter adjustment had caused. The difference was found when the water heads resulting from the parameter adjustment were compared to the water heads found in the reference run. The difference is described in meters and the parameter influence is determined by this number. The larger this number was, the more influence the parameter had on the model results compared to the other parameters. Comparing the effects, and thus of the influences, of the parameter adjustments was done with maps made with the data, using Quantum GIS, and with the medians and averages of the water heads per parameter adjustment.

Parameter adjustment could be easily done as one was allowed to add multiplying factors to values in the input file for the model.

The sensitivity analysis was not stopped when a certain number of runs was reached, but rather by reaching model equilibrium every time a parameter was adjusted. The model was thus run as a steady-state model and a run only stopped when equilibrium was reached in the water balance. The stopping criteria were present for the residual head and the water balance per cell: the closure criterion for the residual head was 0.0001 meter and the closure criterion for the water balance was 10 cubic meters.

3 Background

To understand the model, this chapter features two subjects concerning background information, namely basic groundwater flow principles and the prior Jakarta groundwater studies.

3.1 Flow principles

In the following some basic groundwater flow principles and their influence on groundwater-induced land subsidence are described. Much information described in this chapter originates from the work of Freeze and Cherry (1997). Additional information is provided by other literature.

Groundwater is a part of the water cycle, which can be explained as the hidden water flow, opposing the visible water flow which could be visualized as run off and water bodies, e.g. rivers. Precipitation either comes via run off into water bodies or it gets infiltrated into the soil. From the soil it can go back up via evaporation or capillary action or percolate down into the saturated ground layers, thereby recharging the groundwater volume. The groundwater can also be recharged by leakages in water distribution infrastructure, spills or water bodies. Via groundwater flow, the water comes back to the surface in areas were the piezometric head rises over ground level, or it flows via horizontal flow towards areas with a lower groundwater table. The piezometric head is in most cases the same as the groundwater table. In confined aquifers, the piezometric head often surpasses the groundwater table, as the pressure in this layer is higher due to the weight of overlying ground layers and other loads, and/or due to the hydrostatic pressure generated by the higher parts of the confined aquifer.

In confined aquifers are also flows present, but not only caused by differences in hydraulic head, but also by differences in pressure. Horizontal flow boundaries are then set on points where there is no horizontal flow going beyond or coming from beyond the point. These points are referred to as no flow boundaries. Such points can be found in the high places of a water table, like on the location of the second well from the right in Figure 2, or at objects that interrupt the groundwater flow, like vertical impermeable barriers or watershed points like deep-incising rivers (JWRMS, 1994).

This piezometric head can only be expressed by wells or boreholes with a screen in the confined aquifer, the same as water tables can be determined by monitoring wells and boreholes with a screen in the unconfined aquifer. Aquitards confine the pressure in the confined aquifers, because they consist mostly of materials with a low hydraulic conductivity, e.g. clay, whereas aquifers mostly consist of materials with a high hydraulic conductivity, e.g. sand. Groundwater can be transported through the aquitard in a vertical direction, upward or downward, but this is a very slow process.

Water does not only move through the aquitard, it is also stored within the pores of the aquitard; like aquifers, aquitards can also be drained and recharged. When the hydraulic head drops in an overlying or underlying aquifer by for instance excessive groundwater abstraction, pore water from the aquitard is drained to the aquifer; this results in lowered pore pressures thereby in consolidation of the aquitard. Concluding, the hydraulic head drop in aquifers causes groundwater-induced land subsidence.

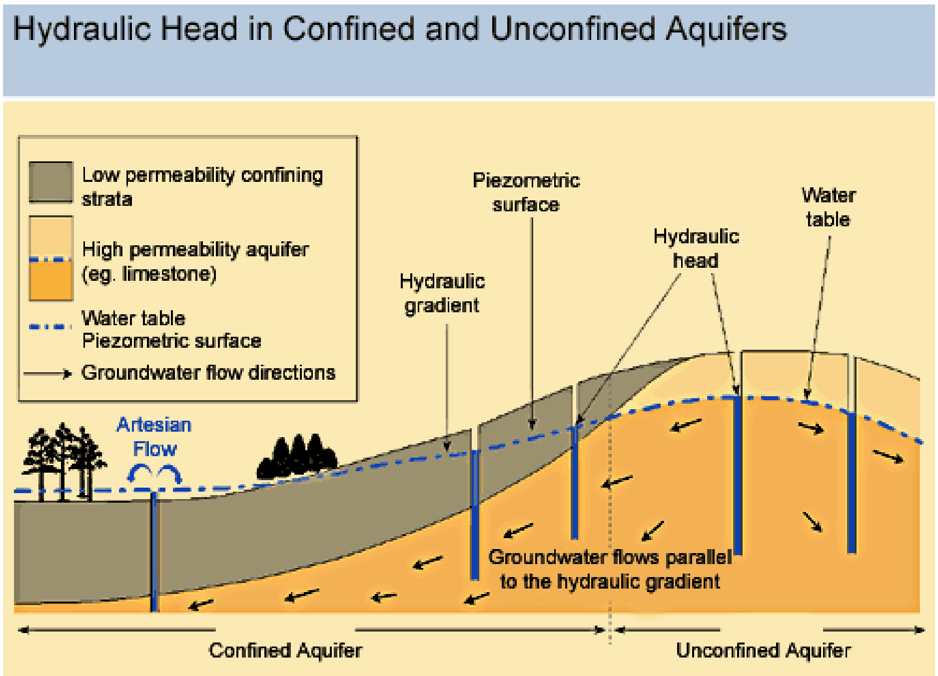


Figure 2. Schematisation of groundwater flow (adapted from: Stewart, Grossman, & McGuire, 2009)

In the many equations describing groundwater, the hydraulic conductivity K plays an important role, in the forms of horizontal hydraulic conductivity K_H and vertical hydraulic conductivity K_V. This parameter is unique for each kind of soil.

The volume of groundwater flow Q [m^3/s] through the aquifer can be described with Darcy's Law times the area A [m^2] through which the groundwater is flowing:

$$Q = A \times -K \times \frac{dh}{dx}$$

The hydraulic conductivity is expressed by K [m/s] and the difference of hydraulic head over distance is described by $\frac{dh}{dx}$ [-]. Hydraulic conductivity is also of importance for determining transmissivity T [m^2/s] for horizontal flow and resistance R [days] to vertical flow.

Not only the hydraulic conductivity is of importance, but also the storativity S of aquifers and aquitards must be acknowledged as it has a vital role in estimating groundwater abstraction-induced land subsidence. For aquitards and confined aquifers, the storativity is described by the specific storage S_S times the thickness of the aquitard or aquifer. For unconfined aquifers, only the specific yield S_y. Mainly the storativity of aquitards and confined aquifers (in other words the specific storage S_S) has a major role in combination with the vertical hydraulic conductivity, as both factors are combined in the consolidation coefficient which is used in the Terzaghi equation (Terzaghi & Peck, 1948) to solve the one-dimensional consolidation equations (JWRMS, 1994). These equations and the Terzaghi equation one of the major methods for determining making groundwater abstraction-induced land subsidence, and were used in multiple subsidence models (Yong et al., 1995; JWRMS, 1994).

3.2 Previous Jakarta groundwater models

In the past, multiple studies have been done about the groundwater system in Jakarta and how the groundwater abstractions influenced the subsidence in the region.

One of the problems previous studies encountered was the complex system of ground layers and their mixtures, beneath Jakarta. Yong et al. (1995) described it as follows: "The geologic setting for Jakarta is seen to be comprised of a complex mixture of aquifers with intercalated clay lenses. The water bearing strata cannot be readily demarcated into distinct aquifers, and the assumption that the entire substrate is water bearing requires a judicious evaluation of the various transmissibility compression coefficients (Yong et al, 1995, p. 93)". This complexity makes it difficult to predict future subsidence and makes it even harder to predict future groundwater abstraction-induced subsidence (Maathuis et al, 1996; Yong et al, 1995; JWRMS, 1994). Other reasons why these predictions were hampered were:

- The lack of a formal stratigraphical framework (Yong et al, 1995);
- The poor quality of the description of sediments by drillers (Yong et al, 1995);
- The lack of (precise) geotechnical/hydrogeological data 40 meters and down below surface (Yong et al, 1995; Maathuis et al, 1996);
- The uncertainties in the distribution of wells and volumes withdrawn (JWRMS ,1994) reported data suggesting the number of unregistered wells is higher than the number of registered wells and that the actual withdrawal volume is higher that the surveyed volume;
- The uncertainty on what lowering elevation benchmarks actually measure (Maathuis et al, 1996).

Different kinds of models were used to describe the system beneath Jakarta, but due to the mentioned obstacles, it was concluded a numerical model should be used. Yong et al. (1995) used a multiple aquifer-aquitard subsidence physical model, which was used as a conceptual model for the analytical groundwater abstraction-induced land subsidence model for Bangkok. When the same conceptual model was used as a basis for a mathematical model, the authors concluded that due to the complex set of layers beneath Jakarta, additional equations were needed for describing groundwater abstraction-induced land subsidence; these equations cannot be solved analytically, but numerically was concluded. According to JWRMS (1994), the reason they used a numerical modelling method was due to the complex layer system under Jakarta which could not be described by an analytical model. Also Soefner et al. (1986) used a numerical model. All discussed models are explained in the concerning studies.

In order (to try) to overcome the described problems, JWRMS (1994) evaluated data about the geotechnical/hydrogeological situation of Jakarta and enhanced it with measurements done during the study. Maathuis et al. (1996) also made a data review in which they included the findings of JWRMS (1994). Both studies offer an overview of values of the available geotechnical and hydrogeological parameters and their qualitative and quantitative uncertainties in the Jakarta study area and also give a distribution for the uncertainty for some values.

3.3 Current Deltares model

A brief introduction to the model was given in section 2.4. More information is given about model in the following.

As said the Deltares model is made with iMOD software. This is done, not only because the Finite Difference Method iMOD was well applicable for the Jakarta groundwater system, but also because of two other reasons: firstly, an iMOD groundwater model could be easily linked to a subsidence model. Deltares engineered both kinds of model software. Linking model results from the groundwater model to the input of the subsidence model thus is easier and less time consuming; secondly, iMOD is open source. This means that the model could be run by everybody, since the software for the model runs is freely accessible.

The outputs of the iMOD model were, among others, a water balance and the water heads. In this study the resulting water heads were used of a model which schematised the groundwater situation in 1992. The reason why the model was made for this year, was because there was, although data was still lacking, more information on parameters available from previous studies for this period than there was for more recent years. This problem would be solved in the future, because the database underlying the model was meant to grow through the years, as more and more data was expected to be collected. At the moment of the study, also a pre-urban period (1900) model was being made. For this model the same database would support it. The 1900 model was however not the model on which the focus laid in this research. Both models were at that moment ran as steady-state models as still not enough data was collected to make adequate time series for which they could run.

The model was placed in a grid representing the study area, see the map in Figure 3. Boundaries of the study area were set on the boundaries of the Jakarta basin. These boundaries were no flow boundaries, which were the Cisadane river to the west, the Bekasi and Cikeas rivers to the east, Jakarta bay to the north and a upward 'bump' in aquifers to the south, which caused a presumed negligible inward flow. Roughly, these were the same boundaries which had been set in the other studies (Maathuis et al., 1996; Soefner et al, 1986).

The distribution of model layers is shown in Appendix A. Of each layer the elevation of the top and the bottom of the layer is shown. In Figure 3 a cross section is shown with the four different layers shown.

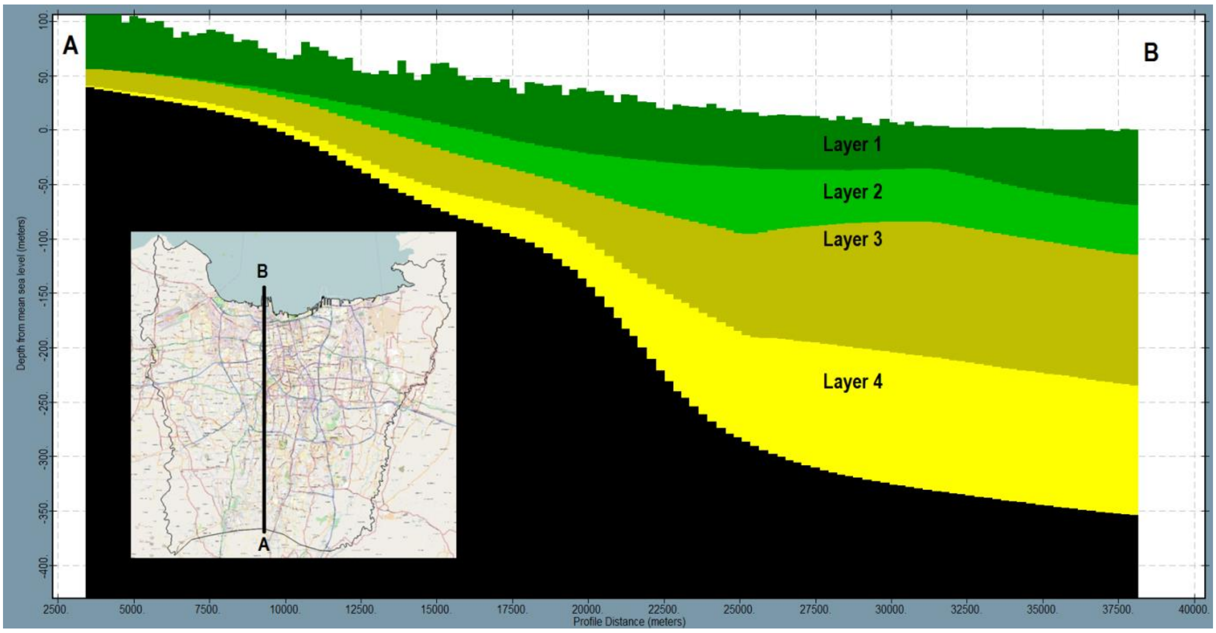


Figure 3. A cross section from south to north of the study area. On the map the boundaries are given

4 Results

In this chapter the results of the research are given. In paragraph 4.1 the parameters used in the steady-state model are given. In paragraph **Error! Reference source not found.** the parameters presented which were used in other groundwater models which were found during the literature study. Finally in paragraph 4.3 the results from the sensitivity analysis are shown.

4.1 Parameters in the model and their values

iMOD runs with different modules and packages, which all use parameters depending on used processes. The modules and packages which are used in this model can be found in Appendix B. With these packages, the following hydrogeological and hydraulic input parameters were included in the model:

- Initial heads in each layer - SHD
- Horizontal hydraulic conductivity (and thus transmissivity) - KHV
- Vertical hydraulic conductivity (and thus resistance) - KVA
- Abstractions - WEL
- Drainage, known and unknown - DRN & OLF
- Discharge to and recharge from rivers - RIV
- Recharge - RCH

Specific storage and the specific yield were not represented in this model as the current model was a steady-state model. In the steady-state run equilibrium, was (tried) to reach for the in and out flow of the model. If the in and out flow are equal, the storage is constant. Specific storage and the specific yield thus played no role in the steady-state model.

It must be mentioned that the KVA tool was in truth a tool with which the anisotropy in the model can be implemented. In the Deltares model, this parameter was used to simulate vertical conductivity. As stated in section 3.2, the geology beneath Jakarta was complex and about this subject not much data was available. Because of this, the precise location and elevation of aquifers was unknown. About aquitards was even less known. Therefor it was decided that the anisotropy of aquifers would be used to simulate vertical conductivity of aquitards. When in the report is referred to the KVA tool, its properties for modelling vertical hydraulic conductivity are meant, except when it is emphatically stated that the anisotropy is meant.

Deltares had used for these parameters certain values, which were on the one hand found in their own data research and collection, and on the other hand adopted from literature and prior Jakarta models. Used values for the parameters in literature and in the Deltares model are shown in Table 1. In Appendix C is the comprehensive version of the table given. Except parameter values, also water balances from literature can be found in Appendix C.8, namely from Soefner et al. (1986) and the JWRMS (1994). These are compared with the water balance from the Deltares model.

Table 1. Parameter values in literature and in the Deltares model

Parameter	Literature	Model
Horizontal hydraulic conductivity	0.1 – 40 m/day (Djaeni, Hobler, Schmidt, Soekardi, & Soefner, 1986)	1 m/day in the north, 1.5 m/day in the centre, 2 m/day in the south, based on values used by Soefner et al. (1986). These values and the locations for the values were the same for all layers
	1.5 to 10 m/day (Yong et al., 1995)	
	1.3 m/day (ILN, 1987; Maathuis, Yong, Adi, & Prawiradisastra, 1996)	
	Mean between 0.4 (north) and 2.1 m/day (south), variates between 0.4 and 4 m/day (Soefner et al., 1986)	
	0.06 to 14 m/day (JWRMS, 1994)	
Vertical hydraulic conductivity	HHC[1]/5000 m/day (north) to HHC[1] /100 to HHC[1] /500 m/day (south) (Soefner et al., 1986)	HHC[1] /833 (layer 1), HHC[1]/1250 (layer 2 and 3) and HHC[1] /1000 m/day (layer 4). Values based on values in the report of Soefner et al. (1986)
	HHC[1] /5000 (north) to HHC[1] /100 (south) (Djaeni et al., 1986)	
	8.6 x 10^{-5} to 4.3 x 10^{-4} m/day (JWRMS, 1994)	
	1.2 x 10^{-4} m/day with a standard deviation of 1.5 x 10^{-4} m/day, < 70 m below surface (Maathuis et al., 1996)	
	in the order of magnitude of 1 x 10^{-5} m/day (ILN,1987)	
Recharge	250 - 1500 mm/year (JWRMS, 1994)	Values ranging from 1642.5 (south) to 255.5 mm/year (north) (Appendix C), being in line with the view of JWRMS (1994) on how much precipitation infiltrates in the soil
Drainage (entrance resistance)	1375 to 2908 days (south) to 352 days (coastal plain) (JWRMS, 1994)[2]	500 m^2/day
River (conductance)	Infiltration when: river level > water head; discharge when: river level < water head (Soefner et al., 1986)	Infiltration when river level > water head, discharge when river level < water head, both cases 700 to 100 m^2/day river conductance (see table C-1, Appendix C)
	Infiltration when river level > water head (5 day resistance), discharge when river level < water head (10 day resistance) (JWRMS, 1994)[2]	
Abstraction	50.3 million m^3/year in 1985 (25.2 million m^3/year registered abstractions, multiplier of 2) (Djaeni, 1985; Soefner et al., 1986)	12.3 million m^3/year in 1992 as used by Maathuis et al. (1996) were used
	38.5 million m^3/year in 1992 (12.8 million m^3/year found, multiplier of 3) (JWRMS, 1994)	
	Multiplier of 2.5 to be applied to registered abstractions (Soetrisno, Satriyo, & Haryadi, 1997)	
	12.3 million m^3/year in 1992 (Maathuis et al., 1996)	

[1] HHC is the horizontal hydraulic conductivity
[2] It was not possible to find the data in JWRMS (1994) to convert the resistance [days] to conductance [m^2/day]

4.2 Parameters used in non-Jakarta models

A literature study has been conducted to give an early identification of the importance of the input parameters. An overview of the results of this literature study can be found in the last two columns of Table 2. In Appendix D an overview of the used models and their set-ups is shown.

Although in reviewed studies no quantified sensitivities were found, the studies proposed four parameters for which groundwater models had major sensitivity, namely the horizontal hydraulic conductivity, the vertical hydraulic conductivity, the (net) recharge, and the abstraction volumes. Of the other input parameters no mention was made or they were dismissed as causing a minor sensitivity in the model (e.g. river input parameters).

In the rest of the four mentioned parameters were focused on to make sure that no resources were wasted on parameters which were already known to have a minor influence.

Table 2. Model parameters, their properties, and their sensitivity in other studies.

Package or module	Parameter	Sensitivity in literature	
		% change parameter	% change model outcome
SHD	Initial water heads		
KHV	Horizontal conductivity of model layers		Major sensitivity (Singh, 2013)
			Major sensitivity first layer (Gedeon, Mallants, & Rogiers, 2013)
			Most sensitive parameter (Kumar, 2013)
KVA	Vertical conductivity of layers separating the model layers		Major sensitivity (Singh, 2013)
			Major sensitivity first layer (Gedeon et al, 2013)
			Most sensitive parameter (Kumar, 2013)
WEL	Abstractions from the model from certain screens		73% of output (Ramalingam, 2001)
			37% of output (Punthakey & Joseph, 2001)
DRN	Abstractions from top model layer when head surpasses certain level		
OLF	Abstractions from top model layer when head surpasses certain level		
RIV	Surface water which either recharges groundwater or gets water discharged in from groundwater, depending on water heads		<1% of input (Ramalingam, 2001)
			21% of input and 39% of output (Punthakey & Joseph, 2001)
		2	0.25 – 20% (Vermeulen et al., 2014)
RCH	Percolation of precipitation into model		83% of input (Ramalingam, 2001)
			73% of input (Punthakey & Joseph, 2001)
			Major input (Seneviratne, 2007)
			Major sensitivity (Gedeon et al., 2013)

4.3 Sensitivity analysis

To make clear the influence of parameter adjustments on the model, maps and graphs have been made. The parameter adjustments were done for the horizontal hydraulic conductivity (KHV), the vertical hydraulic conductivity (KVA), the recharge (RCH), and the abstractions from wells (WEL) parameters. Per parameter adjustment of either factor 2 or factor 0.5 a map was made which showed the change in water heads compared to the water heads resulting from the reference situation run. The maps are prints of the model grid. To determine the change in water head in each cell in the model grid, the following equation was used:

$h_{ij,diff} = h_{ij,adj} - h_{ij,ref}$, with the difference in water head h_{diff}, the water head resulting from parameter adjustment h_{adj}, the water head resulting from the reference situation run h_{ref}, and i and j the corresponding grid coordinates.

In Appendix E, the maps are shown per adjustment for each parameter. The collections of maps are shown per layer. With colours the change is shown per cell, which is either blue and green for positive change, or yellow and red for negative change. With negative or positive is meant that the water level after the parameter adjustment was under resp. above the water heads in the reference situation model run. In Figure 4 the water heads per layer resulting from the reference situation run are shown. Also the wells per layer are shown as black dots.

Sections 4.3.1 to 4.3.4 present the results per model layer. Except for the maps per layer (in Appendix E) also graphs were made, in which per parameter adjustment the median and average values of change are given for all the cells per map. For all medians an overview was provided in section 4.3.5. To not over-generalise the results, a division was made between a northern and a southern part in the study area. The border between the two regions can be seen in Figure 4 as the black line. The derived medians and averages could have caused that positive maximal and negative minimal changes were damped in an average of zero. This was however not the case after reviewing the results. Only outliers were damped. N.B.: These graphs are only provided to give a quick overview of general results deducted from the maps and have to be considerde crude representations of results; the maps must be considered as the main sources of results on which conclusions were based.

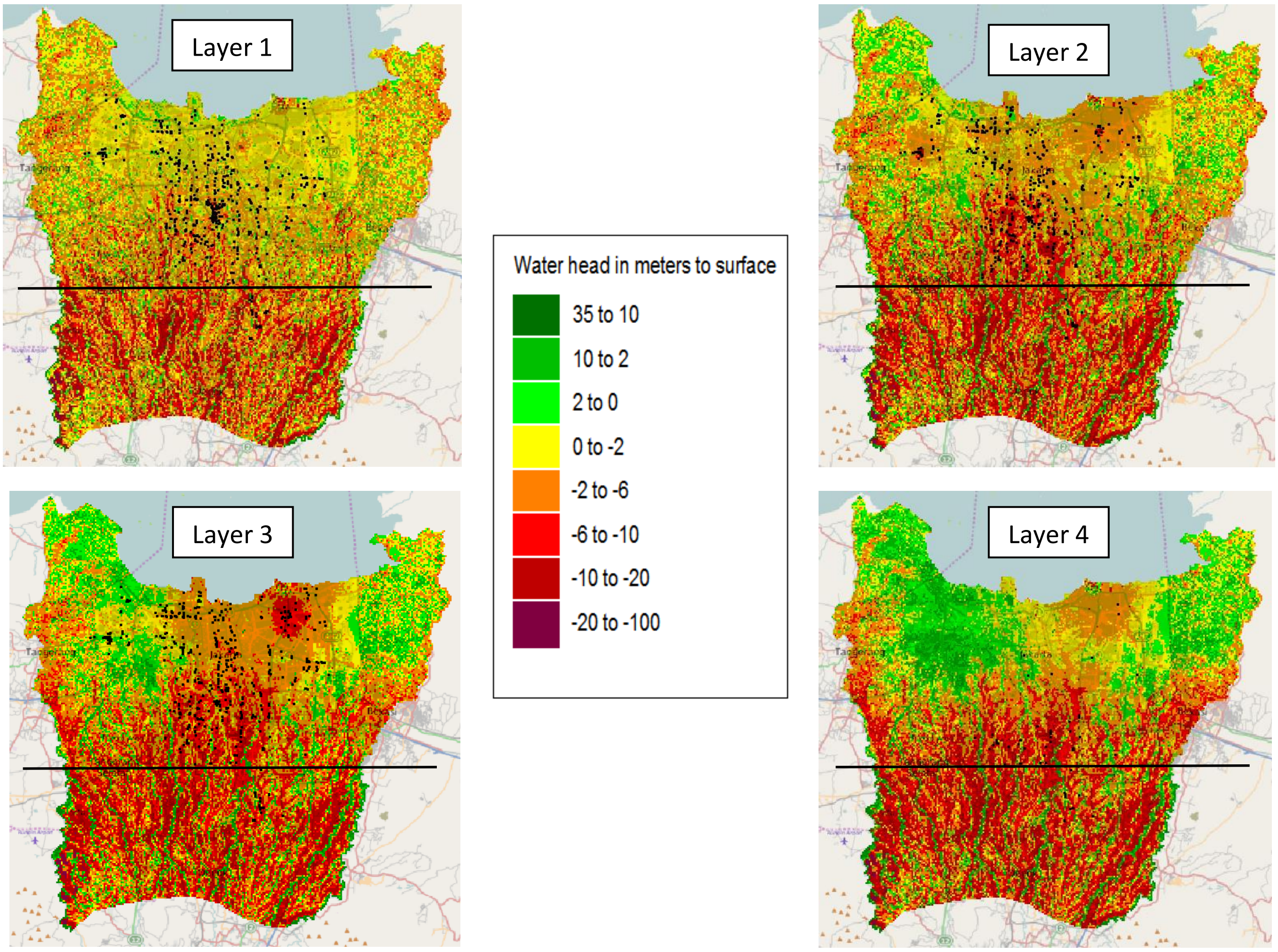


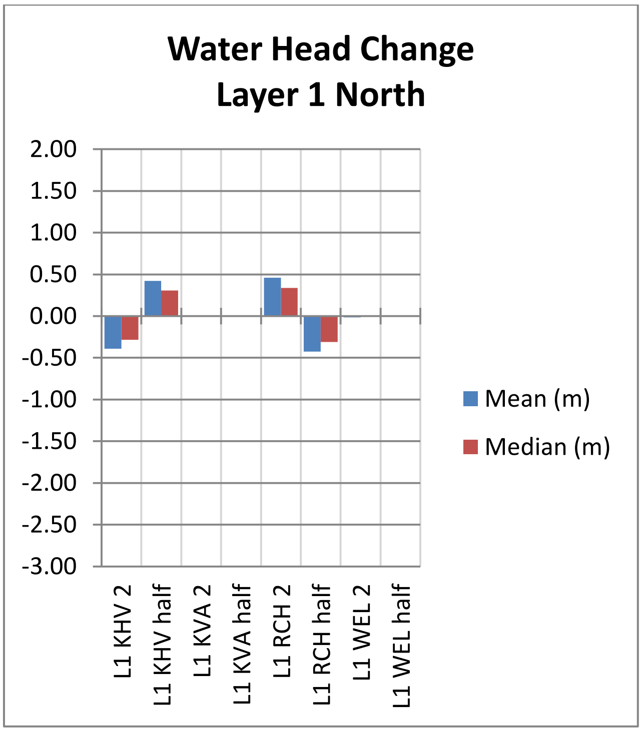
Figure 4. Heads in the Deltares model, relative to the Mean See Level (MSL), with the wells per layer as black points and the division between north and south with the black line

4.3.1 Layer 1

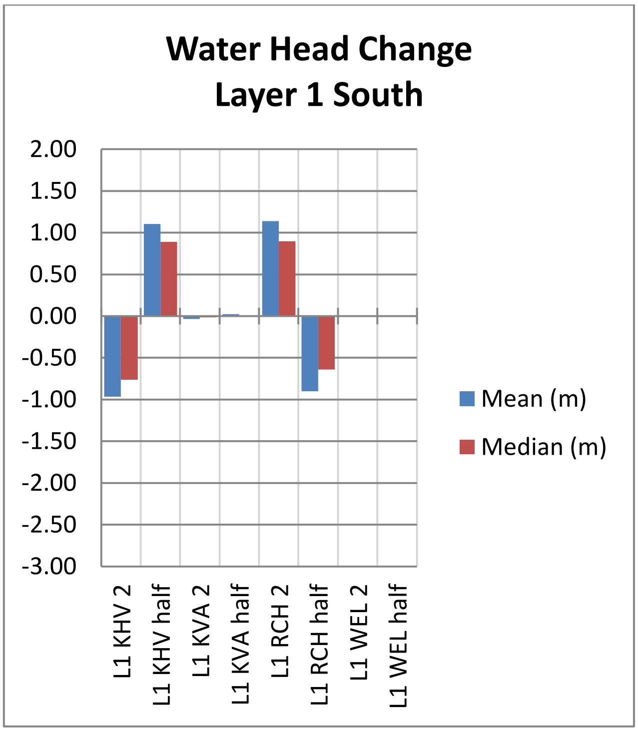
Overall, model layer 1 seemed uninfluenced by the changes of parameter values. The KHV and RCH parameters were most sensitive, with influencing the southern half of the model most. Water heads had an absolute change of 1 to 5 m in this part, whereas in the northern part this was just 0 to 1 meters. This difference between the regions is also described in Figure 5A and Figure 5B, wherein it is shown that changes were approximately two times higher in the south compared to the north. The KVA and WEL tools seemed to have a minor influence in resp. some southern parts and the centre of the study area. That the WEL tool had a minor influence in the south was due to the fact that there were no registered wells located in the south in layer 1. The model layer proved to have a negative change in water heads for all parameters when these were multiplied by two; only for the KVA parameter this was inversed.

Though only being small, there was a positive as well as a negative change when adjusting the KHV parameter in one direction. When the parameter values were doubled, water heads dropped in layer 1, except along the rivers; here the water heads rose. The opposite can be said when the parameter values were halved.

The observed pattern and other patterns were explained in section 5.2.



A.



B.

Figure 5. Water head changes in layer 1 presented by means and medians of parameters. Results are divided in two regions: North (A) and South (B)

4.3.2 Layer 2

In layer 2 a divide was observed between the central and northern part of the layer, and the rest, when variating the KHV parameter. There seemed to be a correlation with the distribution of the abstraction wells, as most wells, if not all wells, are positioned in the northern part. This relation is tried to explain in section 5.2. The relation between well locations and water head change is also seen in Figure 6A and Figure 6B, although not as clear as in Appendix E, as the statistics for the differing northern could not be easily abstracted. Maximum absolute changes in the north were between 1 to 5 meters (KHV factor 2) and 5 to 10 meters (KHV factor 0.5).

This presence of both negative and positive changes in the groundwater heads were also seen when the KVA parameter was adjusted, though not in equal distinction as was seen for the KHV parameter. This difference between roughly north and south can also be seen in Figure 6A and Figure 6B. Maximum absolute changes were 1 to 5 meters.

For the RCH parameter water head changes were either all positive or negative when one parameter adjustment was done. The southern area of model layer 2 seemed to be more sensitive with absolute changes in water heads of 1 to 5 meters. This was affirmed by the map statistics given in Figure 6A and Figure 6B. An explanation for this is given in 5.3.1.

The model layer proved only sensitive to altering abstraction values in the northern half of the model, as is also confirmed by Figure 6A and Figure 6B. Furthermore, when doubling the WEL parameter values, there were even differences in water heads present of -10 to -25 meters, whereas halving the values only caused maximum differences of 5 to 10 meters.

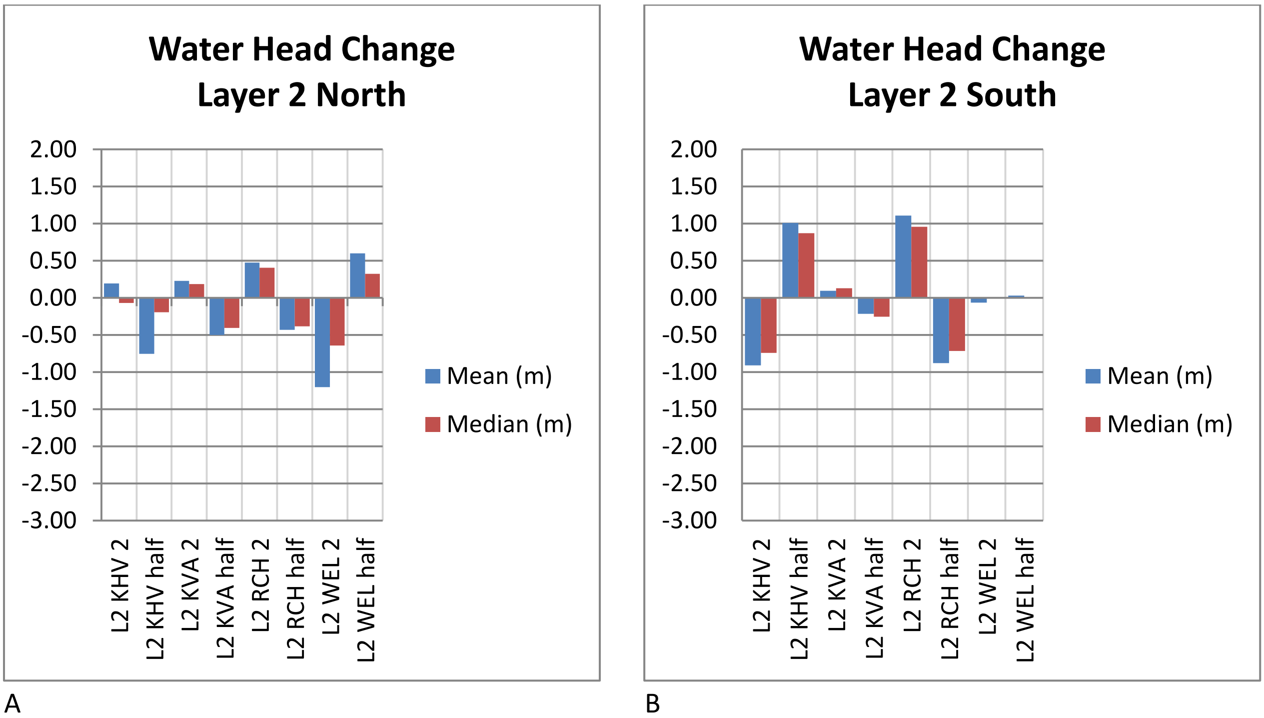


Figure 6. Water head changes in layer 2 presented by means and medians of parameters. Results are divided in two regions: North (A) and South (B)

4.3.3 Layer 3

In layer 3 a distinction was again observed between the area with the positive water head changes and the area with the negative changes when the KHV parameter was adjusted. The distention was already mentioned for layer 2 in section 0, but it became more nuanced in layer 3. There was a large pocket of absolute change of 10 to 25 meter, which was located at the location of a group of wells nearby the junction of the Jalan Tol Pelabuhan and the Jalan Ir. Wiyoto Wiyono Msc. In this point, values were observed to change in a large fashion when doubling and when halving the horizontal conductivity. Changes however were more substantial when halving the KHV parameter values, which can also be said for the rest of the northern region. Also remarkable was the fact that the water head changes of the southern well pocket as seen in the maps had the same sign as the water head changes in the northern half of the layer. In the rest of the south adjusting the KHV parameter caused major water head changes, but not equal to the changes it had caused in the north, see Figure 7. The water head changes of the third model layer for the KVA parameter adjustments were more or less the same as the changes model layer 2 had for these parameter adjustments, which were also located in more or less the same locations. However, when doubling the KVA parameter values, the model layer was more positively changed, whereas negative changes were being more restricted to some parts in the southern half of the layer, and the northeast and northwest corners of the layer. The opposite happened when the vertical conductivity was halved. The major influence of the parameter however was in both cases centred in the central part of the study area.

Sensitivities of the model for recharge were distributed in the same way as was evaluated in sections 4.3.1 and 0, with the major values located in the southern part of the study area. This is shown in Figure 7A and Figure 7B.

The same 'heavy' water head change pocket as was seen for altering horizontal conductivity was also seen when altering abstraction values. Changes were lowest minima in the whole sensitivity analysis when the abstractions were doubled. In the south however the model was not sensitive to altering the WEL parameter, as also is presented in Figure 7A and Figure 7B.

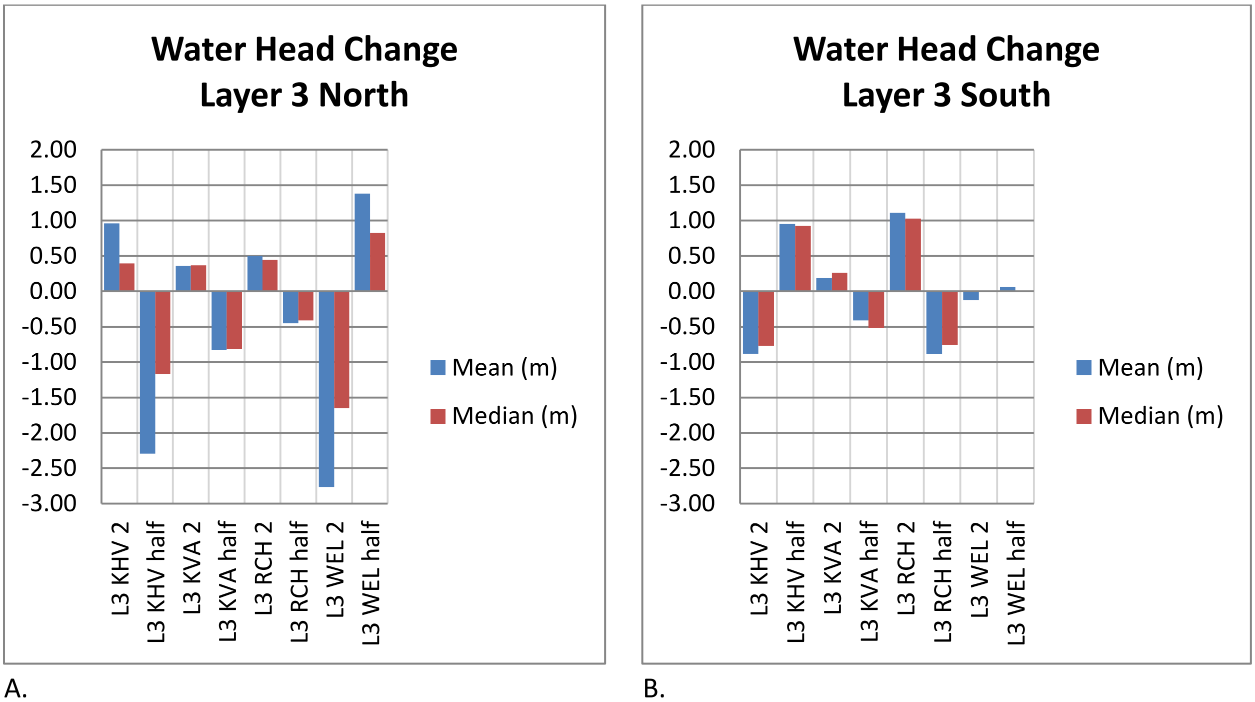


Figure 7. Water head changes in layer 3 presented by means and medians of parameters. Results are divided in two regions: North (A) and South (B)

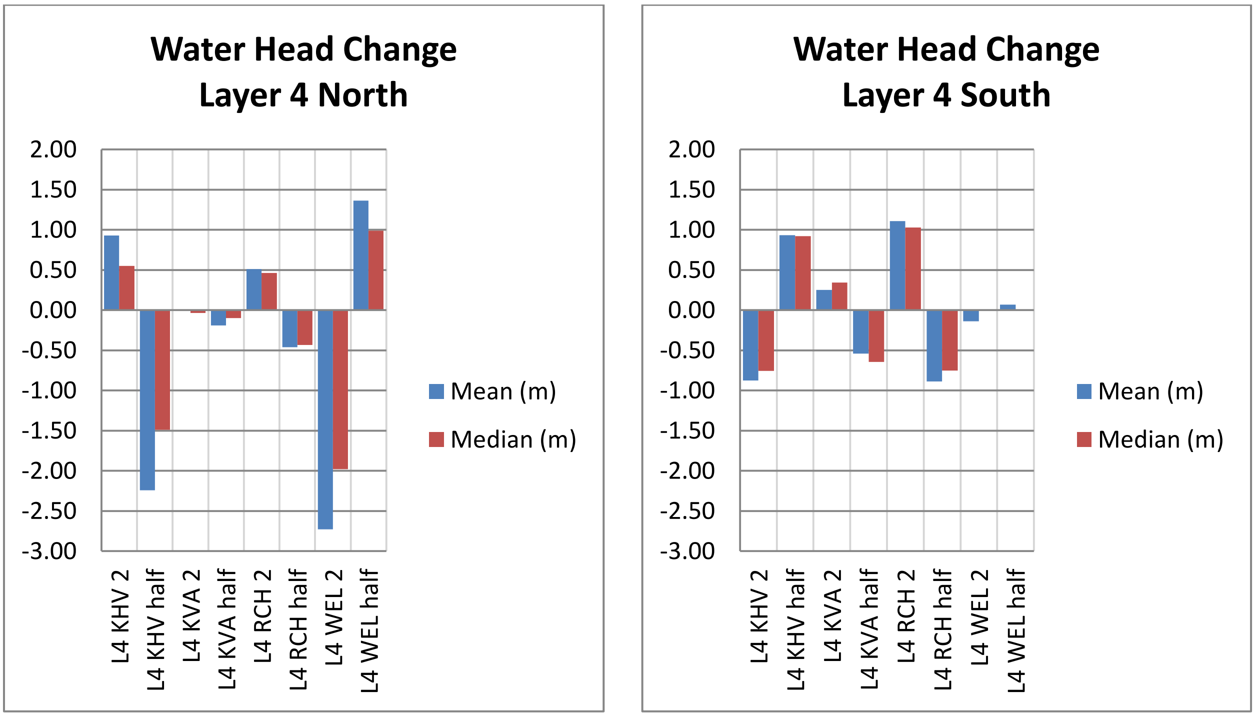
4.3.4 Layer 4

In model layer 4, the positive changes in water heads as a result of doubling the KHV parameter values (and the vice versa for halving the values) again were located in the northern half of the layer with the southern well pocket, however with lesser absolute maxima, these being 5 to 10 meters. The water had changes in the other part of the study area had the inverse sign. Major water head changes were observed around the middle of the coastal plain and had their maximum when halving the horizontal conductivity. The water had changes were also at maximum in the southern part when the KHV parameter was halved. The reason for this water head distribution is given in 5.3.3.

For the KVA parameter values adjustment, three zones of change could be described: the horizontal northern part, the horizontal and southern central part, and some clusters in the latter. When halving the KVA values, the northern part and southern clusters showed negative changes in water heads, whereas the central and southern part showed positive changes. When halving the values, the opposite was true. These values though did not exceed an absolute maximum of 5 to 10 meters. The reason why this distribution was shown is not exactly clear and a flow path analysis should be conducted.

Water head changes in layer 4 for the RCH parameter adjustment were the same as described for layer 2 (section 0) and 3 (section 4.3.3). The alteration of the parameter however caused larger water head changes in the south, compared to the change of water heads when other parameters were adjusted.

The model proved very sensitive to the WEL parameter in layer 4, as was seen in layer 2 and 3. Although there were no extreme water head changes, like in layers 2 and 3, overall the changes in the north of the study area were larger in layer 4 than in layer 3, what one could conclude after comparing Figure 7A and Figure 8A. The southern part of the study area proved, like in other layers, insensitive to this parameter.



A. B.

Figure 8. Water head changes in layer 4 presented by means and medians of parameters. Results are divided in two regions: North (A) and South (B)

4.3.5 Overall

When observing the water head changes in the different layers, differences can be seen in value. In Table 3 a matrix presents all the medians of the water head changes per area and per parameter adjustment. The table offers a crude overview of the data of the maps in Appendix E, and is but a summary of the results. The values shown in the cells are coloured over a range; from red for negative water head changes, via white for no water head changes, to green for positive water head changes. When a value was deep-coloured, it meant that the parameter adjustment caused a large change and thus had a large influence on the model; the paler the colour, the less influence the parameter variation had on the model. Influence could then be translated to sensitivity. This sensitivity can however only be described as the relative sensitivity of the parameter compared to others.

In Table 3, the negative changes for parameter adjustment with factor 2 and with factor 0.5 were odd, but explainable. The negative changes were present for both factors when adjusting the KHV parameter in the northern area of layer 2, and for adjusting KVA parameter in the northern area of layer 4. In both cases, it was determined that this was caused by outliers. Without these outliers, the changes caused by factor 2 could be considered equal to 0.

When Table 3 is observed, conclusions can be made about the sensitivity of parameters on the model. It can be seen that the model was overall the least sensitive to the KVA parameter. Furthermore, the KHV and the RCH parameters influenced the model the most in the southern part of the study area, although the KHV parameter had a major influence in the northern part in the deeper layers. The model was most sensitive to well abstractions, although this influence was only seen in the northern part of the area in the deeper layers.

Table 3. Medians of the water head change (m) per layer

Parameter	Factor	Layer 1		Layer 2		Layer 3		Layer 4	
		North	South	North	South	North	South	North	South
Horizontal hydraulic conductivity (KHV)	2	-0.28	-0.76	-0.07	-0.74	0.39	-0.77	0.55	-0.76
	0.5	0.31	0.89	-0.20	0.87	-1.17	0.93	-1.49	0.92
Vertical hydraulic conductivity (KVA)	2	0.00	-0.01	0.19	0.13	0.37	0.26	-0.03	0.34
	0.5	0.00	0.01	-0.41	-0.26	-0.82	-0.52	-0.10	-0.64
Recharge (RCH)	2	0.34	0.90	0.40	0.96	0.44	1.03	0.46	1.03
	0.5	-0.31	-0.64	-0.38	-0.72	-0.41	-0.75	-0.43	-0.75
Abstractions (WEL)	2	0.00	0.00	-0.64	0.00	-1.65	0.00	-1.98	0.00
	0.5	0.00	0.00	0.32	0.00	0.83	0.00	0.99	0.00

5 Discussion

In this chapter a reflection is given on the methodology, on the results, and on patterns in the results of the sensitivity analysis. In the two first sections a distinction is made in the reflection on the literature study and the sensitivity analysis

5.1 Methodology

Literature research

In section 2.5.1 it was explained that literature would be used for describing an early identification of sensitivities of parameters. This also meant that models made for other systems than the Jakarta groundwater system were reviewed. Comparing different models seems questionable, but as can be read in Appendix A most reviewed studies also made use of MODFLOW software, the same software as the Jakarta model uses. This is however no justification as there were no in-depth analyses done into similarities and more importantly the differences with the Jakarta groundwater system due to a lack of time. Likewise the review of studies on the Jakarta groundwater basin for an early sensitivity analysis could be questionable. The study area may be more or less the same; schematisation of the system however is different. Still the literature study was done as a selection of parameters had to be made to narrow done the scope of the sensitivity analysis.

Sensitivity analysis

Remarks can be made in the methodology of the actual sensitivity analysis. The factors 0.5 and 2 variance used for the analysis were chosen for a univariate analysis. More degrees of variance would have fitted the bandwidths found in the literature study, and multivariate analysis would have been more appropriate as the analysis of the model suggested that parameters were dependent on each other. The parameter estimation tool included in iMOD could have implemented a more elaborate sensitivity analysis. Instead a manual method was chosen, because of the time available for the study. Also it was considered that a complex analysis would be poorly spent on the current simple version of the model. The state of the model was also a prior anticipated risk, but the current state of the model allowed the rather simple analysis method to be conducted.

Besides, the factors 0.5 and 2 were in hindsight poorly chosen. With these factors unequal bandwidths on both 'sides' of the initial value were provided. Because of this, the results of the parameter adjustment with factor 0.5 could not be compared with the results of the adjustment of the same parameter with factor 2; no conclusions could be drawn on the influence of the direction of the parameter adjustment.

5.2 Results

Literature study

In literature parameter sensitivities were found, only remained questionable if the information could be used and what validity the information had for the research. The research on parameter values was however considered sound and its results were a good addition to the overview Maathuis et al. (1996) made, but the found bandwidths could not be included in the sensitivity analysis. Reviewing literature took a considerable amount of time, since the literature on the Jakarta studies was vaster than anticipated, and finding relevant articles for the early sensitivity analysis proved difficult. In addition, when reviewing literature it was not taken in account how many times the article was referred to in other literature. In this way, validity of sources may not be solid, but due to the scarcity of found literature it was one of the last options. Though this literature presented (mostly qualitative) sensitivities, never were all counterparts found to the parameters in the iMOD model. It was however likely that validity of the selection of parameters made in the early sensitivity analysis was unaffected by this fact; the parameters in this selection were appearing in most studies, which meant that they have been playing a significant role in modelling groundwater systems.

Sensitivity analysis

Multiple obstacles and dilemmas were perceived during the sensitivity analysis which were beforehand not anticipated. Also patterns were observed in the maps, which were tried to explain. One of the major problems during the study proved to be the defining of northern and southern areas of the study area. Where the border between the areas would be defined in the analysis was decided in the review of the different maps in the different layers, but due to the linear nature of the border the location was still not satisfying as the two areas could not be so easily uniformly separated. Eventually the border was located with the rule of the thumb rather than with a scientific process.

Another obstacle in the analysis was the fact that the impact of the parameter adjustments on the horizontal flow through the study area was missing. The model proved to be in a major way sensitive to the RCH parameter, especially in the southern area, but it seemed odd that the lower aquifers were influenced in the same way as layer 1 was influenced, since only layer 1 received directly the recharge. A theory might be that the deeper layers were recharged horizontally from the southern part. Water in these parts could reach deeper layers as in the model in the southern area 1) the deeper layers had a relatively high elevation, 2) the thickness of all layers was small, and 3) the conductivity in the southern area was larger than in the northern area. The assumption though that the northern area of deeper layers was recharged via a lateral flow from the south, was more or less dismissed in the JWRMS model (JWRMS, 1994). A last remark however must be made about the recharge rate on its own: the general recharge might be considered a bit insignificant compared to a doubling of recharge.

The results for the other parameters than the recharge parameter in the sensitivity analysis were anticipated, although they were expected to be higher. That the change in the horizontal conductivity parameter had influence in all layers was perceived normal, also the conclusion that the change in the abstraction parameter influenced the water heads most in a certain radius around the wells. The maxima and minima shown especially in the latter were anticipated, but the effect of variating the other parameters was thought a bit low. It was expected that with changes of 0.5 and 2 the overall change would be more than just a few meters. The effects of the adjustment for the vertical conductivity parameter were especially thought low.

Besides the analysis of difference in water heads also an analysis was attempted of the change per parameter adjustment of the water tables per layer. Results were gained, but these proved to be incomplete and not scientifically sustainable, thus these were decided to not include in the report.

5.3 Patterns in the results of the sensitivity analysis

There were expectations about the total analysis results, but there were no expectations about the patterns that were seen per parameter adjustment. These patterns were tried to explain.

5.3.1 Layer 1

In the maps of layer 1, certain areas had larger head changes when parameters were adjusted, and then mostly in the southern areas. The reason for this could be explained by the combination of two factors: the characteristics of the terrain and the difference in conductivity. The southern areas in the model were sloped more, since more hills and river valleys were present when compared to the northern area. This caused steeper gradients in the local water table. When for instance the horizontal hydraulic conductivity was increased, it meant that groundwater could flow faster to lower areas in the layer as is learned from the Darcy's Law (presented in section 3.1). The rate at which the groundwater flowed was further increased by the steep gradients in the sloped, southern areas. The higher grounds in these areas were drained faster than the flat, northern areas. This large difference of water heads was in the southern areas also present when hydraulic conductivity is halved.

The second factor which played a role in the large head changes in the southern areas was the difference in value of the horizontal conductivity, and indirectly of the vertical conductivity. In Appendix C.1 it was explained that a higher horizontal conductivity was used in the southern areas of the study area than in the northern area. This was derived from literature. When a multiplier of 2 or 0.5 was used, the change of the larger values in the southern area caused a larger absolute change, thus meaning that there was more effect in the south than in the north when the parameter is adjusted.

Similar to the results of the change of the KHV parameter were the results of the change of the RCH parameter. Although with adjusting this parameter all water head changes had the same sign, the results also showed in the southern area a relation with the geography. When the recharge was changed, water head chances between cells in the hills were larger than that in the cells in the valleys or below the rivers. In the normal model run, the hills would be recharged but due to gravity a part would flow down. The valley and river cells would not only have recharge from the recharge parameter, but also from cells with a higher elevation. When the recharge was doubled, the hill cells received more water than could be discharged to lower cells, resulting in a new and higher water head in these cells. Although more water was also discharged to lower lying cells, it seemed that the influence was not as big. When however the recharge was halved, the hill cells were cut in their input, but due to the steep gradients of the sloped terrain, discharge still occurred towards lower lying cells. Thus the hill cells were drained and their water head was lowered. Valley or river cells were also halved in their recharge, but still water was coming in from cells with a higher elevation. Water heads also were lowered, but in a smaller fashion than was the case with the hill cells.

When adjusting the KHV parameter a reverse change in water heads was seen when comparing river cells with other cells. This could be explained by the fact that, when the KHV parameters were doubled, the excess water in the first layer from e.g. recharge could flow faster to points of discharge like the rivers, thereby draining the soil but increasing the water heads in cells under/near the river. That the excess water in these cells could not be discharged straight away was due to the resistance present for discharge from the soil to drainage or rivers. When the KHV parameters were halved however, excess water flows slower to points of discharge. Because of this, cells under/near the rivers got drained, and subsequently a drop in water head in these cells was caused. These lowered water heads could not be compensated with water from rivers, since there was a resistance present for infiltration from rivers.

5.3.2 Layer 2

In the maps for layer 2 (and 3), a relation was observed between well locations and the sign of the water head changes when the KHV parameter was adjusted. This relation between well locations and the sign of the water head changes could be explained by the lower water heads around abstraction wells. Due to this, groundwater in the layer flowed to these points. When the horizontal conductivity was enlarged, water from the surrounding area flowed faster to abstraction wells, thereby increasing the water levels around wells, but draining the surrounding areas, in other words, the areas not belonging to the north or central study area. The opposite was true when the hydraulic conductivity is reduced.

It seemed for layer 2 that the southern area was more sensitive to variations of recharge. An explanation for a similar observation in layer 1 was already explained in section 5.3.1, but it may not fully explain the cause of the high influence of recharge adjustment. Another explanation might be offered with the cross section of the study area, shown in Figure 3. In this graph, one could see that in the north the model layers 2, 3 and 4 were in the southern area thin and close to the surface. Water from recharge was then more easily flowing via layer 1 to the deeper layers than was the case in the more northern parts of the study area. The influence of the adjustment of recharge is therefore not only seen in the southern area of layer 2, but also in layers 3 and 4.

5.3.3 Layer 4

In maps for layer 4, the distribution of water head changes with maxima located in the southern area was probably majorly due the fact that groundwater flowed towards the area with lower heads. When hydraulic conductivity was reduced, groundwater flowed slower to places with low heads, in other the words, the northern part of the study area. Heads in the north would drop as wells kept abstracting and the northern area of the layer was recharged slower by horizontal flow. The higher grounds, mainly the south, were not drained of as much water as in the reference situation, so heads rose. The opposite of this explanation is true when doubling the KHV.

6 Conclusion

The research question of this study was: “To which extent is the groundwater system of Jakarta, like calculated in the groundwater model, sensitive for the parameters of the groundwater model?” Multiple steps were taken in order to answer this question. It was established that there were 7 input parameters used in the model, namely the initial water heads per layer, the horizontal hydraulic conductivity, vertical hydraulic conductivity, abstractions, drainage, recharge, and discharge from and recharge to rivers. In literature mostly qualitative sensitivities of groundwater models were found. With this literature study a selection was made of 4 parameters to likely have a major influence on the model, namely horizontal hydraulic conductivity, vertical hydraulic conductivity, recharge, and abstractions. With this selection a univariate sensitivity analysis was carried out with a variance of factors 0.5 and 2.

The sensitivity analysis had the changes in water heads due to parameter adjustment as outcome. The recharge parameter seemed in all layers very sensitive relative to the other parameters, but mostly in the south because of the geology of the system. This parameter had also a large influence on lower aquifers, which seems odd as recharge occurs from the surface. The abstractions had the largest influence when compared to the other parameters. This large influence was only present in the north though, where the majority of wells were situated. The vertical hydraulic conductivity parameter also had its influence, but only ‘polarised’ the layers, since the water heads in some parts rose and in other parts lowered. This happened in the same parameter alteration. The same happened with the horizontal conductivity parameter, though in less extend; a distinction was observed between the central coastal plains and the rest of the region. In both parts obvious change was seen.

In the end it can be concluded that the water heads in the ground water model were overall most sensitive to the horizontal hydraulic conductivity and recharge parameters in the south, and the northern parts of the deeper layers were most sensitive to the abstraction parameter. An important remark was that the sensitivities were all relative to the sensitivities of the model for the other parameters.

Based on the results of this study, it is recommended for Deltares that for the overall model more research should be into horizontal hydraulic conductivity in the whole study area, with which a more detailed, layer specific map can be made to use as input for the horizontal hydraulic conductivity parameter. Besides, an extensive research should be done into the well abstractions, which could be restricted to the industrial parts of the city, which are located mainly in northern districts. In these locations the large, deep wells are located and if their location and abstraction volumes are known, the large sensitivity of the model for the abstraction parameter will have fewer consequences for modelling results.

7 Recommendations

In this chapter recommendations are made for future research.

Some recommendations for a more elaborate sensitivity analysis are in place. For this multiple options are offered. A multivariate analysis in the bandwidths found in this study should be done in a sensitivity analysis for a future version of the model. If the resources allow it, adjusting the parameters should be done per layer instead of for all layers at once. These recommendations could be implemented in future research if the state of the model and the complexity of the model allow the elaborate sensitivity analysis built in the parameter estimation tool in iMOD.

For studies which will be done with this research as its base, also recommendations can be given. Firstly, a flow path or horizontal flux analysis should be done to determine the amounts of water flowing through a layer, and from one area to another. Also, in this research was the zoning a subject of discussion. It would be of much use for a researcher if this is properly done. This is especially true when continuing with an uncertainty analysis, in which it is important to know which locations of the study area have a high uncertainty in the results. With this information focused data collection can be carried out.

8 Bibliography

Argo, T. A. (1999). *Thirsty Downstream: The Provision of Clean Water in Jakarta, Indonesia*. University of British Comlubia, Vancouver. Retrieved from http://www.watergovernance.org/documents/WWW_PDF/2010/thursday/T3/Legal_and_policy_development_water_quality_the_right_to_water_riant_nugroho.pdf

Balasubramanian, A. (2001). Overview of Groundwater Model. In L. Elango & R. Jayakumar (Eds.), *Modelling in Hydrogeology* (1st ed., pp. 17–24). Mumbai: Allied Publishers Limited.

Booij, M. J. (2014). *Inleiding Waterbeheer | Modelleerlijn*. Enschede: University of Twente.

Chaussard, E., Amelung, F., Abidin, H., & Hong, S. H. (2013). Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction. *Remote Sensing of Environment*, *128*, 150–161. http://doi.org/10.1016/j.rse.2012.10.015

Deltares - Taskforce Subsidence. (2013). *Sinking cities - An integrated approach towards solutions*. Delft.

Djaeni, A. (1985). *Water Demand and Water Supply for DKI Jakarta with Special Reference to Groundwater Extraction* (No. 100). Bandung.

Djaeni, A., Hobler, M., Schmidt, G., Soekardi, P., & Soefner, B. (1986). Hydrogeological Investigations in the Greater Jakarta Area/Indonesia. In *Proceedings of the 9th Salt Water Intrusion Meeting* (pp. 165–176). Delft: Delft University of Technology. http://doi.org/ISBN-90-800089-1-5

Erlangga, E., Soefner, B., & Zaepke, J. (1985). *Evaluation of DEG-Well Files 1874 - 1984: Aquifer Parameters and Piezometric Heads, Groundwater Properties* (No. 102). Bandung.

Freeze, R. A., & Cherry, A. (1979). *Groundwater*. Englewood Cliffs: Prentice Hall.

Gedeon, M., Mallants, D., & Rogiers, B. (2013). Building a staircase of confidence in groundwater modeling : a summary of ten years data collection and model development. In *MODFLOW and More 2013: Translating Science into Practice* (pp. 545–550). Golden: Integrated Groundwater Modeling Center. Retrieved from http://www.researchgate.net/publication/248706152_Building_a_staircase_of_confidence_in_groundwater_modeling_a_summary_of_ten_years_data_collection_and_model_development

Goorden, N. (2015). *First report on Jakarta Groundwater Model*. Bandung.

Indec & Associates Ltd., Lavalin international Inc., & Nippon Koei Co. Ltd. (ILN). (1987). *Cisadane River basin feasibility study. Groundwater. Volume 3*. Jakarta.

IWACO, DHV Consultants, Delft Hydraulics, TNO, Persero P. T. Indah Karya, P. T. Kwarsa Hexagon, & P. T. Wiratman & Associates. (1994). *Jabotabek Water Resources Management Study (JWRMS). Final Report. Volume 6*. Jakarta.

Kumar, C. P. (2013). Introduction to groundwater modeling. *Journal of Hydrology*. Roorkee: National Institute of Hydrology. http://doi.org/10.1016/0022-1694(83)90201-9

Maathuis, H., Yong, R. N., Adi, S., & Prawiradisastra, S. (1996). *Development of groundwater management strategies in the coastal region of Jakarta, Indonesia. Final Report*. Ottowa.

Punthakey, J. F., & Joseph, S. (2001). Assessing Groundwater Management Strategies for The Lower Murray Region, Australia. In L. Elango & R. Jayakumar (Eds.), *Modelling in Hydrogeology* (1st ed., pp. 93–102). Mumbai: Allied Publishers Limited.

Ramalingam, M. (2001). Groundwater Modelling of Kallar Watershed, Tamilnadu, India. In L. Elango & R. Jayakumar (Eds.), *Modelling in Hydrogeology* (1st ed., pp. 103–114). Mumbai: Allied Publishers Limited.

Ravi, R., Ballukraya, P. N., & Thaugarajan, M. (2001). Mathematical Modelling of Chennai Area Aquifer System. In L. Elango & R. Jayakumar (Eds.), *Modelling in Hydrogeology* (1st ed., pp. 81–91). Mumbai: Allied Publishers Limited.

Schmidt, G., Tirtomihardjo, H., & Koehler, G. (1985). *Groundwater Modelling* (No. 116). Bandung.

Seneviratne, A. A. A. K. K. (2007). *Development of Steady State Groundwater Flow Model in Lower Walawa Basin -Sri Lanka*. International Institute for Geo-information Science and Earth Observation. Retrieved from https://www.google.nl/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CCEQFjAA&url=http://www.itc.nl/library/papers_2007/msc/wrem/amarasinghe.pdf&ei=DfxiVfLmN5K_uASvnYOgCg&usg=AFQjCNH0JqhZE7NhD--03-dGydGck4RsNQ&sig2=uEFWY4-dfS

Senthil Kumar, M., & Elango, L. (2001). Numerical Simulation of Groundwater Flow Regime in a Part of The Lower Palar River Basin, Southern India. In L. Elango & R. Jayakumar (Eds.), *Modelling in Hydrogeology* (1st ed., pp. 115–126). Mumbai: Allied Publishers Limited.

Singh, A. (2013). Groundwater modelling for the assessment of water management alternatives. *Journal of Hydrology*, *481*, 220–229. http://doi.org/10.1016/j.jhydrol.2012.12.042

Soefner, B., Hobler, M., & Schmidt, G. (1986). *Jakarta Groundwater Study 1983 - 1985. Final Report*. Hannover.

Soetrisno, S., Satriyo, H., & Haryadi, T. (1997). To Anticipate Impacts of Reclamation of Jakarta Bay. In *Workshop on Coastal and Nearshore Geological/ Oceanographical Assessment of Jakarta Bay: A Basis for Coastal Zone Management and Development*. Jakarta: Directorate of Environmental Geology. Retrieved from http://www.geocities.ws/Eureka/Gold/1577/reclamation.html

Stewart, R., Grossman, E., & McGuire, J. (2009). Groundwater - The Sea Beneath Our Feet. Retrieved April 22, 2015, from http://oceanworld.tamu.edu/resources/environment-book/groundwater.html

Syaukat, Y., & Fox, G. C. (2004). Conjunctive Surface and Ground Water Management in the Jakarta Region, Indonesia. *Journal of the American Water Resources Association*, *40*(1), 241–250. http://doi.org/10.1111/j.1752-1688.2004.tb01022.x

Terzaghi, K., & Peck, R. B. (1948). *Soil mechanics in engineering practice*. New York: John Wiley.

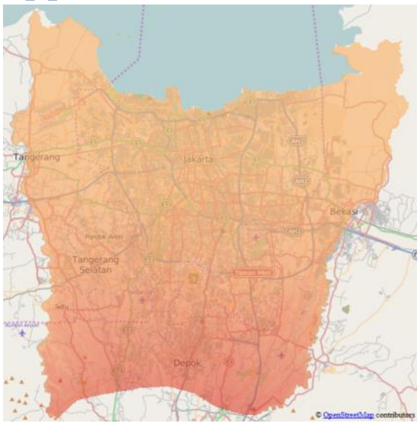
Ting, C. S., Zhou, Y., de Vries, J. J., & Simmers, I. (1998). Development of a preliminary groundwater flow model for water resources management in the Pingtung Plain, Taiwan. *Ground Water*, *36*(1), 20–36. http://doi.org/10.1111/j.1745-6584.1998.tb01062.x

Vermeulen, P., Van der Linden, W., & Minnema, B. (2014). *iMOD - User manual* (3.0.36988 ed.). Delft: Deltares.

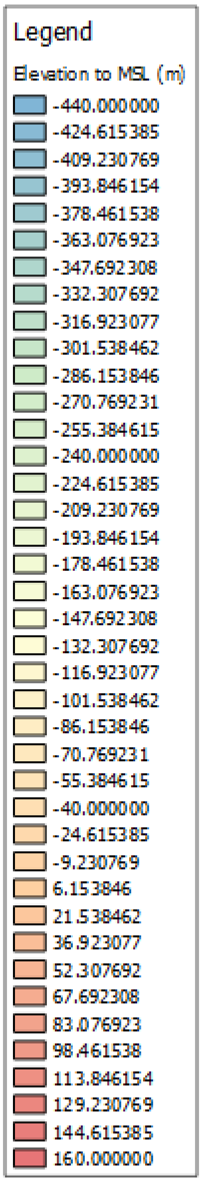
Yong, R. N., Turcott, E., & Maathuis, H. (1995). Groundwater abstraction-induced land subsidence prediction : Bangkok and Jakarta case studies. *Land Subsidence*, *234*(234), 89–97.

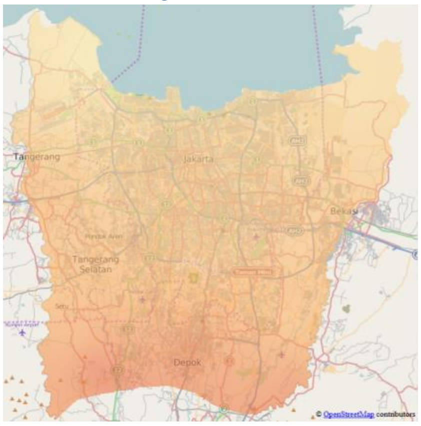
Appendices

Appendix A: Elevation the top and bottom of model layers

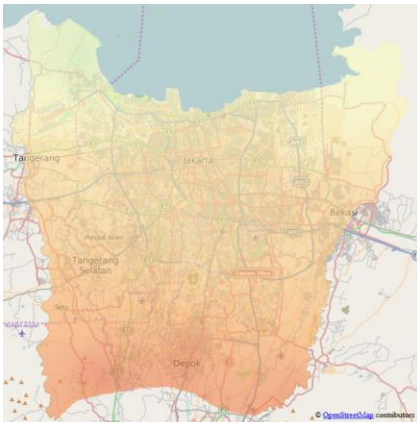


Top layer 1

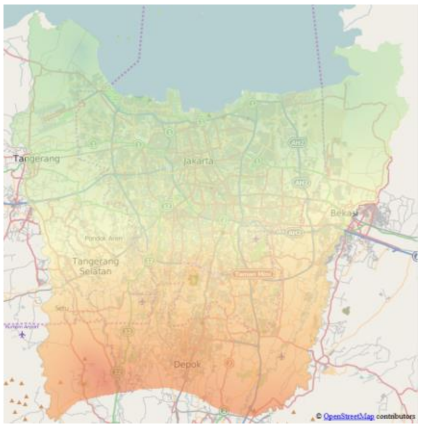




Bottom layer 1 – Top layer 2

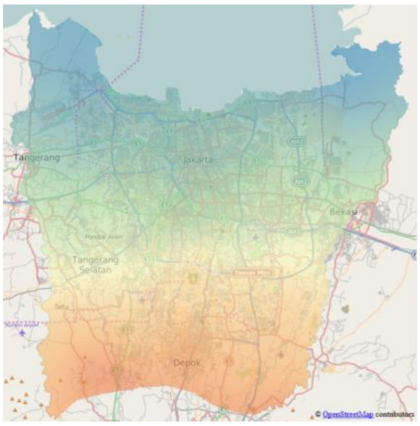


Bottom layer 2 – Top layer 3



Bottom layer 3 – Top layer 4

These elevation maps are shown here as the boundaries between the different model layers in the Deltares model (Goorden, 2015).



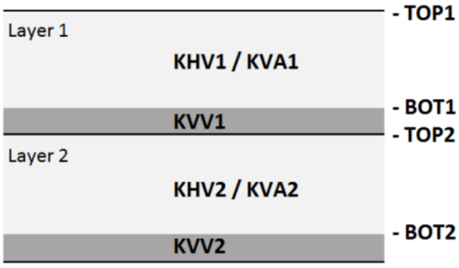
Top layer 4

Appendix B: iMOD modules and packages used in the model

iMOD modelling software contains multiple packages and modules to use as building bricks for the model. What the function and the theoretical background of these modules and packages are, are described in the iMOD manual (Vermeulen et al., 2014).The following packages and modules of the iMOD modelling software were used in the model:

- BND – Boundary conditions
  - Describe for each model layer for each cell whether it is
    - An area with a fixated head. Values in the cell remain unchanged by the model (boundary value < 0);
    - An area excluded from the simulation. In these areas no groundwater is flowing (boundary value = 0;
    - An area which takes part in the simulation. In these cells groundwater flow and head are computed (boundary value > 0).
  - Value:
    - IDF
  - Correspond with the IBOUND values in MODFLOW BAS package
- SHD – Starting Heads
  - This module describes the starting head being the distance from the groundwater level relative to the surface in each cell of each model layer at the start of the model run.
  - Values:
    - IDF (elevation relative to mean sea level)
- TOP – Top of aquifers
  - Values:
    - IDF (elevation relative to mean sea level)
  - TOP variable in MODFLOW DIS package
- BOT – Bottom of aquifers
  - Values:
    - IDF (elevation relative to mean sea level)
  - BOTM variable in MODFLOW DIS package
- KHV – Horizontal permeabilities
  - In this module the horizontal conductivity, in distance per time unit, of each model layer is described. Transmissivities of model layers can be calculated per cell in combination with the resulting model layer thicknesses from the defined top and bottom boundaries of the model layers.
  - Values:
    - IDF
  - HY variables in MODFLOW BCF package
  - HK variable specified in MODFLOW LPF package
- KVA – Vertical anisotropy for aquifers
  - Herein the dimensionless vertical anisotropy is defined. Vertical anisotropy is a coefficient which describes how much the vertical conductivity of a model layer or aquifer differs from the horizontal conductivity. When multiplied with the horizontal conductivity, it results in the vertical conductivity of the model layer.
  - Values in model:
    - IDF
  - VKA variable in MODFLOW LPF package

- KVV – Vertical permeabilities
    - The vertical conductivity of the layers between the model layers, the aquitards, is described with this module. In combination with the thickness, resulting from calculating the distance between the bottom of one model layer and the top of the underlying model layer, the vertical resistance of the aquitards can be determined
    - Values
        - Model layer 1 – 2: 0.0004
        - Model layer 2 – 3: 0.0002
        - Model layer 3 – 4: 0.00035
    - HY variable in MODFLOW BCF package
    - VKCB variable in MODFLOW LPF package



Transmissivity (m^2/day) = KHVn * (TOPn – BOTn)
Vertical resistance (days) = (BOTn – TOPn+1) / KVVn + 0.5 * (TOPn – BOTn) / (KHVn * KVAn) + 0.5 * (TOPn+1 – BOTn+1) / (KHVn+1 * KVAn+1)

Figure B-1. KHV, KVV, KVA, TOP and BOT tools explained

- WEL – Well package
    - Abstractions of groundwater from the model are simulated with wells. These wells have certain well screens, which defines from which depth a volume of groundwater per time unit is abstracted in distance units.
    - Values
        - IPF with coordinates, mean abstractions (m^3/s) and the top (m) and bottom (m) of well screens
- DRN – Drainage package
    - This package defines the location, the elevation in distance units and the conductance in distance square units per time of the drainage system. This system represents drainage pipes and drainage ditches by which water is removed from the model when the calculated head in a model layer exceeds the elevation of the drainage system. On the other hand, when the River package is used in combination with the Drainage package, drainage becomes inactive in cells in which surface water is simulated with a water level surpassing the drainage elevation level.
      As drainage mostly takes place in the top layer of a system, in the model the drainage package is usually only linked to the first model layer.
    - Values
        - 500 m^2/day (conductance of the drainage system)
        - IDF (elevation relative to mean sea level)
- OLF – Overland flow package
    - Like in the Drainage package, in this package an elevation can be set, which, when surpassed by the groundwater head, simulates a discharge of water out of the

groundwater system. This water however does not ‘disappear’ via a drainage system, but is simulated as water running over the surface. It is used as a system to replace the unknown drainage though. In actual study area, this creates nuisance.

    - Values:
        - IDF (elevation relative to mean sea level)

- RIV – River package
    - With the River package permanent water bodies are simulated in the model. Water in the water bodies can infiltrate in underlying layers or water from underlying layers can get discharged into the water body. However, in the groundwater model rivers are not simulated as flowing media of water but rather as inexhaustible sources of water or insaturable points.

      Of these water bodies are per cell given the water level, the bottom level of the water body, the conductivity from water to or from underlying layers in distance square per time units, and the dimensionless infiltration factor. Values for this factor determine when infiltration takes place:
        - = 0 – no infiltration takes place
        - > 0 – infiltration takes place when the water head in the cell is lower than the water level
        - < 0 – infiltration only takes place when the water head is below the bottom level
    - Values:
        - River 1, 3 to 6 resp. 700, 500, 300, 200 and 100
        - 2 IDF’s with water and bottom levels for 5 rivers (relative to mean sea level)
        - 1 (infiltration factor)
- RCH – Recharge package
    - The percolation of precipitation to groundwater in distance per time units is described in the Recharge package.
    - Values
        - IDF, with the following values for recharge: 0.6849, 1.7123, 2.3973, 3.0822, 3.7671, 4.7945, 6.1644 and 8.2192 mm/day

Appendix C: Comprehensive version of parameter values in literature

Of importance is to know what in literature is said about the values and the bandwidths of the input parameters. In this way, when conducting the sensitivity analysis, one sees what values, used in the model, are realistic and what are not. These values for the Jakarta groundwater system can be derived different previous reports. The values will be evaluated per parameter. The report of Maathuis et al. (1996) already gives an excellent overview of most of the sources and was used as support while the data from different sources was compiled in this chapter.

C.1 Horizontal hydraulic conductivity

Djaeni et al. (1986) stated that the horizontal hydraulic conductivity to be between 0.1 and 40 m/day. Yong et al. (1995) determined this to be between 1.5 m/day to 10 m/day. Maathuis et al. (1996) and the ILN (1987) used values with an average of 1.3 m/day. Soefner et al. (1986) used the same average of 1.3 m/day, but also stated that it varies between 0.4 to 4.0 m/day. They also mentioned that this mean varies from 0.4 m/day in the north to 2.1 m/day in south Jakarta. JWRMS (1994) concluded after tests that conductivity ranges from 0.06 to 14 m/day. All authors base their values on data received from local Indonesian institutions, or found in borehole surveys and pumping tests. However, the amount of boreholes used was unlikely to give full coverage of the whole study area; already multiple times it has been expressed that the geological system beneath Jakarta is very complex. Qualifying horizontal conductivity is often determined by what kind of soil is found at certain depths. It is safe however for an early, simple model to use found values or base values for horizontal conductivity on known boreholes. When a more complex model would be made though, more research must be done into input values for the KHV parameter.

In the model, used values were based on the values Soefner et al. (1986) used. The values the authors presented in their report were relatively complete when comparing to other works, what was important since horizontal conductivity is an important parameter. The distribution of values can be seen in Figure C-1.

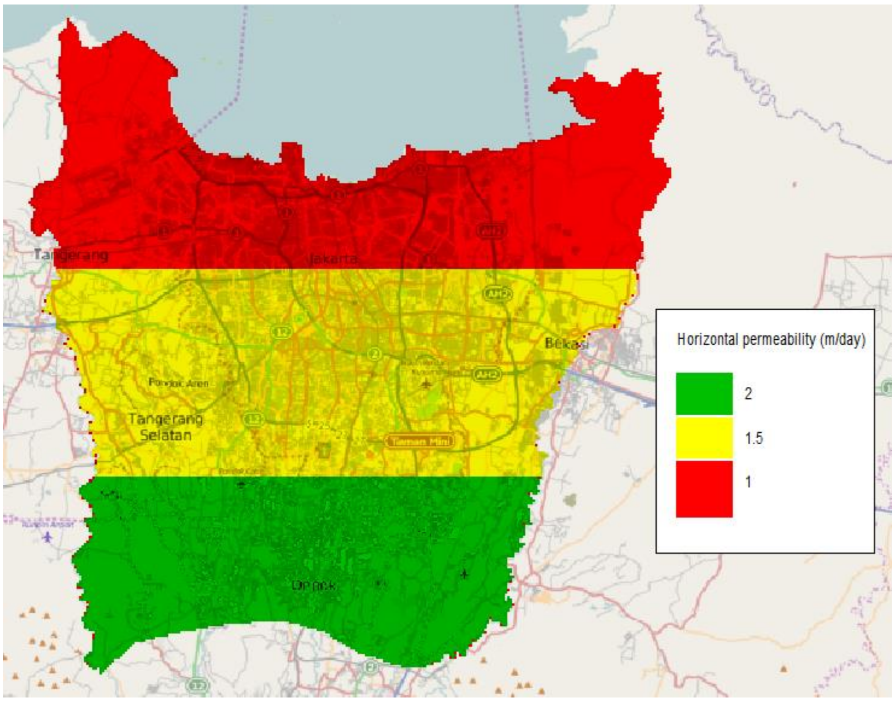


Figure C-1. Distribution of horizontal conductivity values

C.2 Transmissivity

Though this is a parameter is calculated with model layer thickness and horizontal conductivity in the model, in many literature values for this parameter are often mentioned. Therefore, an overview is also provided for this parameter. However, parameter values are only included when model layer thicknesses are given. Only then it can be correlated to horizontal conductivity.

Erlangga et al. (1986) made a synoptical block diagram in which the different transmissivities are stated per layer. This diagram can be found in Appendix F. "ILN (1987) uses similar values (Maathuis et al, 1996, p. 20)." JWRMS (1994) states however that these values are two times too high. Their values for transmissivities were placed in a finer grid, what can be seen in appendix D in annex 6 of their report. They however stated that the values were still too high, but this was unavoidable during model calibration. Maathuis et al. (1996) observed the similarity in multiple models of a reduced transmissivity towards the coast, but evaluated that most researchers based this on speculation and not only on data, since it was lacking.

C.3 Vertical hydraulic conductivity

Soefner et al. (1986) estimated the vertical hydraulic conductivity to be 1/5000th of the horizontal conductivity for the confined system situated above the latitude of 93.05. For the system between the latitudes 93.05 and 90.2, they estimated the vertical hydraulic conductivity to be between 1/100th and 1/500th of the horizontal conductivity. These values were also used for the upper 100 m of the system above latitude 93.05. Djaeni et al. (1986) also suggested the values to be between 1/100th and 1/5000th of the horizontal permeabilities. JWRMS (1994) used vertical hydraulic conductivities of 8.6×10^{-5} m/day to 4.3×10^{-4} m/day. Maathuis and Yong (1994) however concluded that a vertical conductivity was present of 1.2×10^{-4} m/day (with a standard deviation of 1.5×10^{-4} m/day) for the soil above 70 m depths, but that there is no data for ground layers with an elevation lower than 70 m below surface. ILN (1987) suggested less precise values, though they agree that the values should be in the order of magnitude of 1×10^{-5} m/day (or 1×10^{-9} m/s).

Similar to the horizontal hydraulic conductivity, also values for the vertical hydraulic conductivity are taken from the HAG report of Soefner et al. (1986). These values however were input for the anisotropy tool, which was also used for simulating vertical conductivity, like explained in section 4.1. In literature, approximately the same values for anisotropy were found as were found for vertical conductivity. It can be concluded that using the tool for both input parameters does not cause any problems in the first version of the model.

C.4 Recharge

All literature (Soefner et al, 1986; JWRMS, 1994, Djaeni et al, 1986; Maathuis et al, 1996; Yong et al, 1995) indicate that recharge in the 1990 situation took place over the whole study area, instead of seeing natural recharge and discharge zones.

Schmidt et al. (1985) regarded the shallow aquifer as fully recharged by rain and the recharge was to be calculated with the amount of rain that fell, which could be calculated with the method shown in Appendix G. The mean annual rainfall would be 2000 mm, meaning that the recharge would be 2000 mm/year of the shallow aquifer. Delinom (2008) stated the annual rainfall to be between 1500 and 2500 mm/year, which was more or less the similar to the HAG recharge parameter (Schmidt et al, 1985). JWRMS (1994) integrated runoff from paved and developed urban areas in the model during rains. In this way, recharge of the shallow aquifer in their model was a percentage of the rainfall, rather than that the recharge of the shallow aquifer was equal to the precipitation. The distinction was made between recharge from pervious surfaces and the recharge from impervious surfaces. The method with which recharge was calculated, can be found in Appendix H.

Whereas Schmidt et al. (1985) only could give a qualitative evaluation on the downward leakage from the shallow aquifer to the underlying aquifers, JWRMS (1994) made an approximation of percolation of rain water, which was 15% to 20% of the shallow aquifer recharge. They however only gave the percentage for the area between Depok and the northern border of Jakarta Selatan. They also stated that “the major part (75% to 80%) flows up again towards the shallow aquifers e.g. below rivers (JWRMS, 1994, annex 10, p. 35).” With these values, they calculated that the recharge of the deeper aquifers is only 4% of the shallow aquifer recharge. Soetrisno et al. (1997) estimated the rainfall to have an average of 1730 mm/year and the recharge to deeper aquifers to be 1.05% of the rainfall, thus 18.25 mm/year.

Besides rainfall and upward flow, it is also suggested that the shallow aquifer is recharged by leakage from septic tanks and losses from the piped water system (Argo, 1999; Maathuis et al., 1996). For PAM Jaya, the piped water distributer, the amount of unaccounted for water has been and is 50% (Argo, 1999; Syaukat & Fox, 2004), which made the loss of water 5 m^3/s in 1997, 157,68 million m^3 in total for the whole year (Argo, 1999). Of course illegal taps made up for a part of the losses, but faulty connections between pipes and cracks in pipes would probably have contributed to the losses for a large part. This means that a certain amount of water would have recharged the shallow aquifer; however, it is not known where exactly the pipes are located. Besides, their effect on the recharge of the aquifer can only be assumed, since no research has been done into this subject. This is also true for the effect of leakage from septic tanks on the recharge of the shallow aquifer. De Vries (2015) determined that 72% of the Jakarta households used a septic tank and assumed that 80% to 120% of the daily used volume of groundwater from these households would leak from the septic tanks into the shallow aquifer. Besides De Vries, no other research was done into the impact of sceptic tanks on the recharge of the shallow aquifer.

Recharge values used in the model were 5 values, decreasing roughly from the south to the north. This recharge is only the recharge from rain, as recharge from leakage is already taken in account in another part of the model. What these values are and how they are distributed in the study area, can be seen in Figure C-2. These values correspond with the values JWRMS (1994) used as the recharge due to rainfall in 1990.

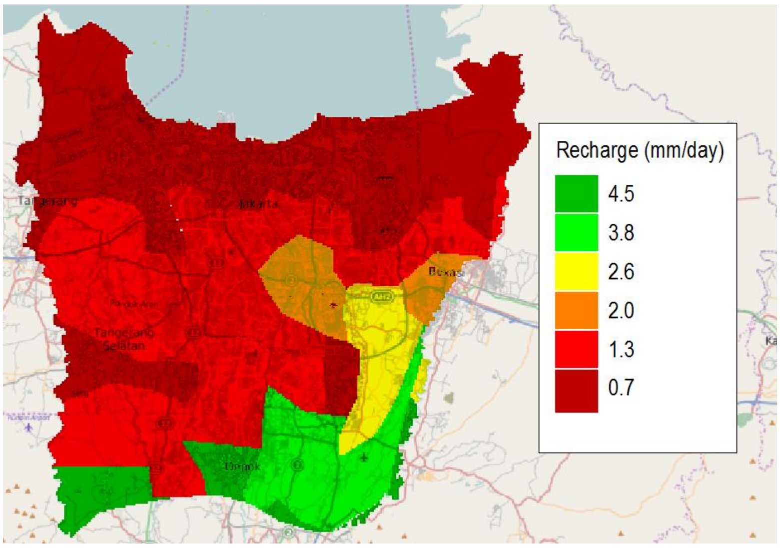


Figure C-2. Values for recharge and their distribution

C.5 Discharge

Only the JWRMS (1994) mentioned the implementation of drainage systems in Jakarta. For drainage, the resistance for an outflow to the surface varied from 1375 to 2908 days in the locations were volcanic fan was present in the shallow aquifer, and 352 days in the coastal plain. It was however unknown how far the volcanic fan really reached and JWRMS had to make assumptions on this, because the information deducted from existing boreholes did not give a decisive answer. Maathuis et al. (1996) also reflects on this shortcoming, which is one of the many caused by lack of data.

Discharge systems were included in drainage and overland flow. Deltares did get a map of the drainage system, though the location of drainage is only known for the Jakarta region and not for the whole study area. The information for the drainage system originates from the Balai Besar Ciliwung-Cisadane, the water board which is concerned with the Ciliwung and Cisadane basin in DKI Jakarta. For the drainage system, a conductance of 500 m^2/day is given. The known drainage system is given in Figure C-3 as it is implemented in the drainage tool. Where the location of the drainage system is unknown, the OLF package (Appendix B) offers a way of implementing the drainage system by ensuring water heads do not exceed the level of 1 meter above surface.

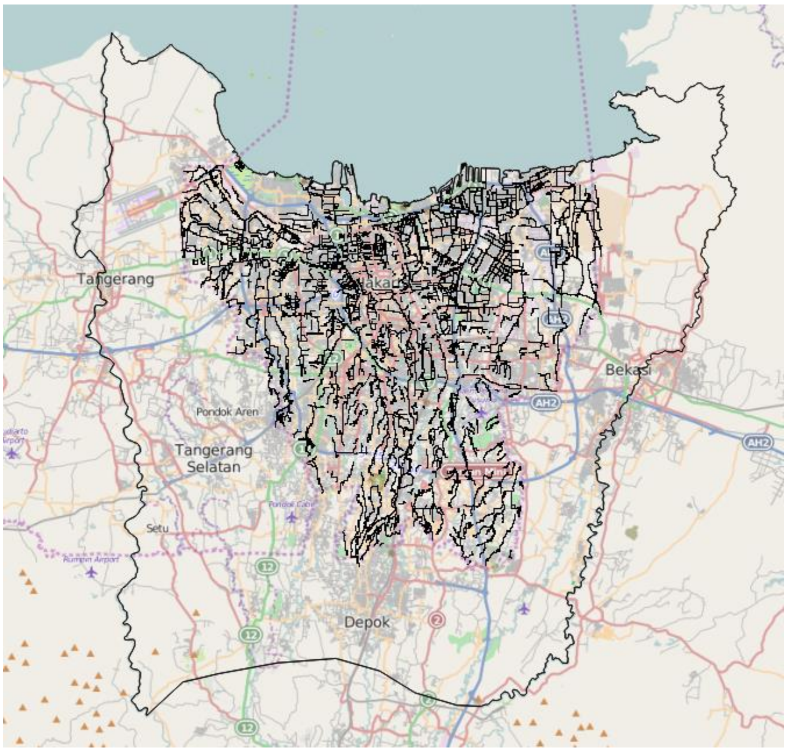


Figure C-3. Drainage system in model

C.6 Rivers

Rivers were before not mentioned in the sections about recharge and discharge, as they have to be mentioned separately, because they have their place in both recharge and discharge.

Soefner et al. (1986) assumed in their model that there was a discharge from the shallow aquifer to surface water when the water table was above river levels and that there was a recharge of the shallow aquifer when surface water levels were higher than the water table. JWRMS (1994) used the same assumption for this model, only they worked with resistance coefficients which determined how much discharge from or recharge to the shallow aquifer there was. For a flow from the river into the aquifer a resistance of 5 days was stated, for a flow vice versa 10 days. The wet perimeter of rivers was varied with the elevation of river beds river beds going from 10 m below surface in south to 0.5 m below surface.

Since rivers can clearly be observed, data of rivers and their characteristics could be regarded as solid and as useful for modelling the 1992 model. However a side note must be made for future modelling: the rivers in Jakarta may be subsiding at the same rate as the rest of the city, but since outlets to sea become sparser and outflow to sea is dependent on pumps, the river system in the north of the study area is prone to sedimentation. Because of this, wet perimeters are reduced, thus interaction between rivers and the groundwater system is also reduced. Dredging activities can solve this, but the current policy is focused on enlarging water capacity in rivers by heightening riverbanks with sheet piling. Capacity in rivers may be increased, but the effective wet perimeter will not be increased as contact area stays the same.

For the Deltares model, river data from JICA (1983), the Flood Hazard Mapping Framework made by Deltares for PU DKI and Balai Besar Ciliwung-Cisadane and Badan Informasi Geospasial were used. In the model the different river branches are categorised as shown in Table C-1.

Table C-1. River data

River Network	Water Level relative to surface level (m)	River Depth relative to surface level (m)	River conductance (m^2/day)	Colour in Figure C-4
Type 1	- 1.5	-10	700	Red
Type 2	- 1	-8	500	Blue
Type 3	- 1	-8	300	Green
Type 4	- 1	-7	200	Orange
Type 5	- 1	-5	100	Purple

In the last column, the colours of the rivers are shown with which they correspond in Figure C-4.

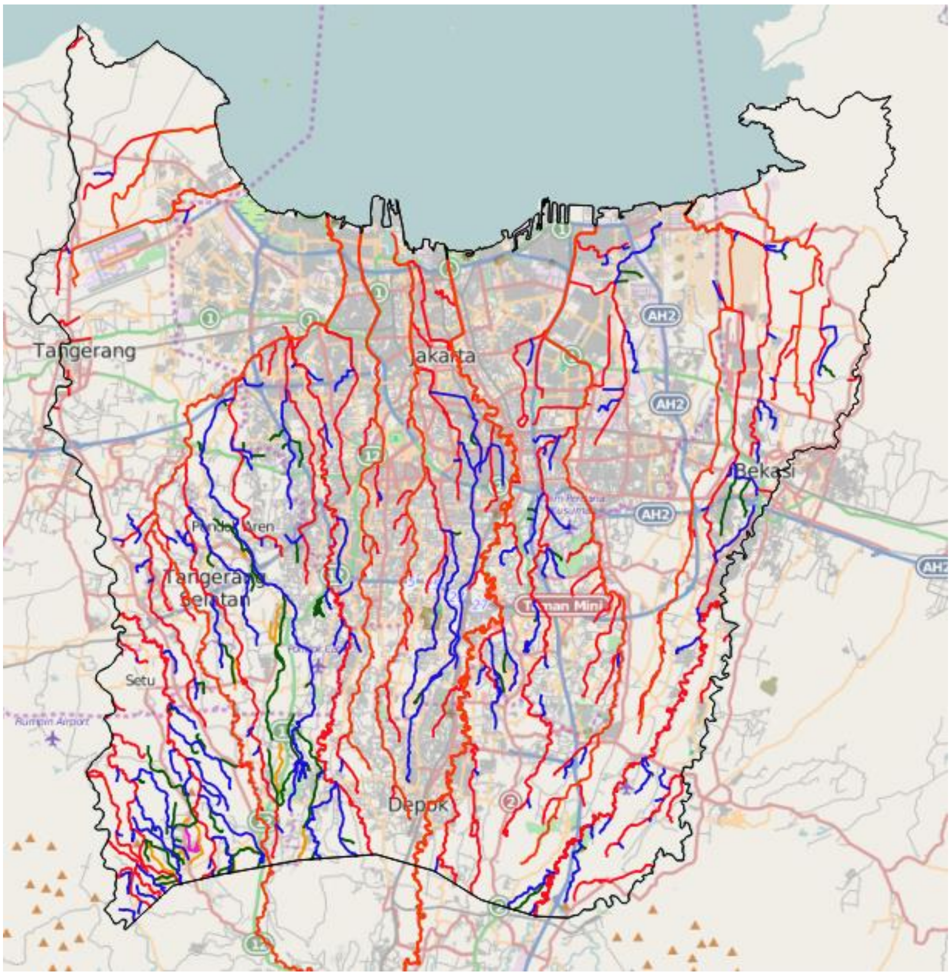


Figure C-4. Rivers used in the model

C.7 Abstractions

Integrity of abstraction data is by all literature doubted. In the years before the mass urbanisation and industrialisation however, abstraction data seems more reliable. In Appendix I two figures can be seen. In figure H-1 the data of HAG (Djaeni, 1985) can be seen plotted against the registered abstractions graph of BPLHD (Badan Pengelolaan Lingkungan Hidup, or Environmental Management

Agency), which seems to coincide fairly well, only the years 1963, 1968, 1973 and 1982 seem odd, as the values or considerably larger than the values registered by BPLHD. The differences in the years 1976 and 1977, and 1979, 1980 and 1981 may be overlooked as the large difference is caused due to the fact that Djaeni (1985) only had time series in their data in these years. However, Soefner et al. (1986) suggest that the actual water abstraction is 200% the registered abstraction, since they observed that “registered abstraction figures seem not to be very reliable (Soefner et al, 1986, p. 37).”

Further doubts are there also about the abstraction data from later years. In Appendix J can the difference in abstraction values be seen between real abstractions and registered abstractions at registered wells in table I-1, and between abstractions of unregistered wells and the real abstractions of registered wells. This data was gathered for deep groundwater wells in 1992 by JWRMS (1994). They concluded that in the end a multiplier of 2.23 was needed to get from the registered abstraction volume to the real abstraction value. They however used a multiplier of 3 in their model for the input for abstractions as they regarded this to better simulate the real situation.

Soetrisno et al. (1997) however said that the deep groundwater abstractions at unregistered wells JWRMS found was too small, and stated that unregistered abstractions in 1995 were at least 1.5 times the registered abstracted volumes. According to Soetrisno et al. (1997), the real deep groundwater abstraction thus had a multiplier of 2.5, without already taking shallow groundwater abstractions into account.

For the abstractions, well data from Maathuis et al. (1996) and the BPLHD were used. For the actual abstracted volumes no multiplier was used. Locations and the abstraction from wells are shown in Figure C-5.

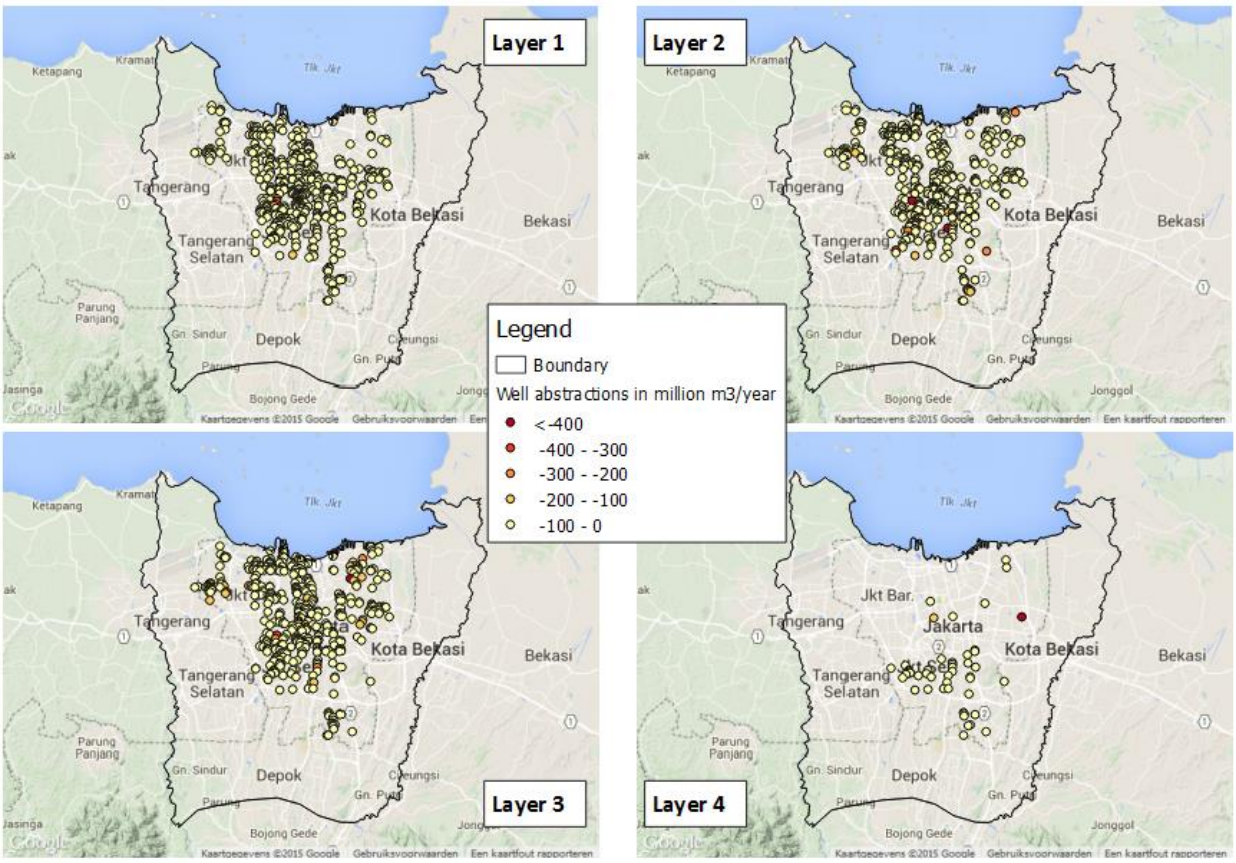


Figure C-5. Well locations per layer and quantification of abstractions

C.8 Water balances

As said, the HAG and JWRMS reports looked into the Jakarta situation and made models for simulating past and present states of the groundwater system for Jakarta, and for predicting future scenarios. In their results, they also included water balances, e.g. for the 1985 and 1990 situations.

C.8.1 HAG 1985 model

The conceptual model of the HAG reports can be seen in Figure C-6. Q1 represents the discharge to and infiltration from rivers, Q2 infiltration from or discharge to the surface/shallow aquifer, and Q3 the abstraction.

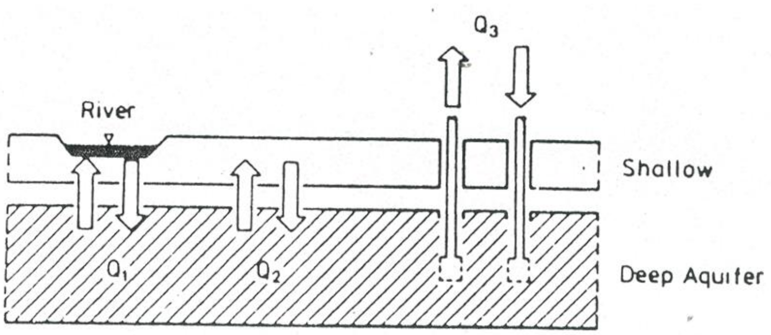
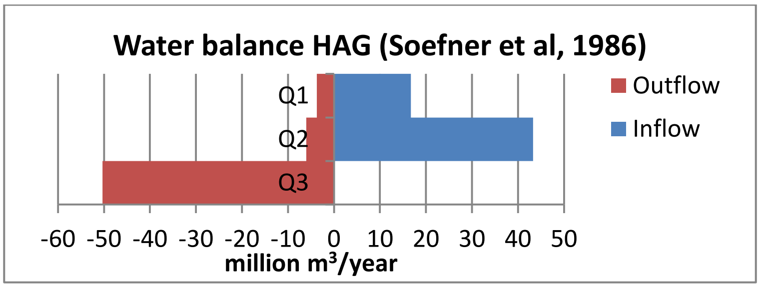


Figure C-6. Concept model water balance HAG (Soefner et al, 1986)

In Table C-2 the total amounts of water of these water flows can be seen. One can see that the major inflow comes from infiltration and that the major outflow is represented by groundwater abstractions.

Table C-2. Water balance HAG (Soefner et al, 1986)

Flow	In (million m^3/year)	Out (million m^3/year)
Q1	16.7	-3.7
Q2	43.3	-6
Q3	0	-50.3
Total	60	-60



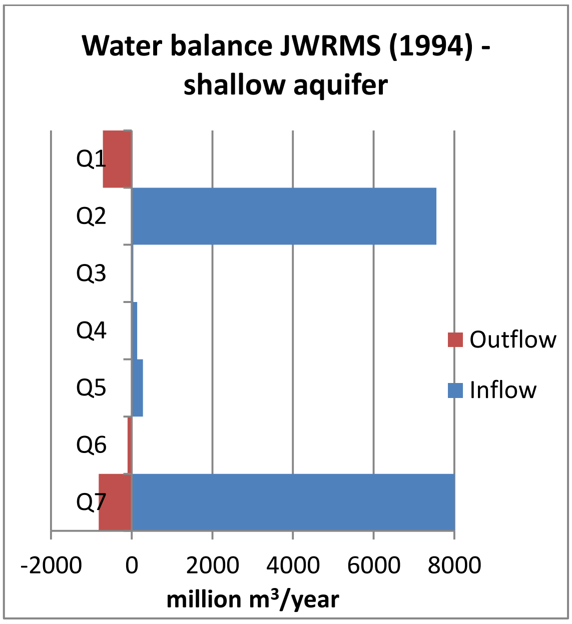
The HAG water balance however is very difficult to compare with the water balances of Deltares and JWRMS, as the conceptual models for the water balances are too different, mainly because of the different schematisation of the top layer and the more or less direct interaction between rivers and the deep aquifers.

C.8.2 JWRMS model

In the JWRMS report is no total water balance to be found, only the water heads resulting from model runs. However, there was a Shortage Risk Index made, it which parts of the water balance for the shallow aquifer were featured. With these an incomplete water balance for the shallow aquifer could be made, which can be seen in Table C-3.

Table C-3. Incomplete water balance of the shallow aquifer of the JWRMS model

Shallow aquifer	In (million m^3/year)	Out (million m^3/year)
Abstraction shallow aquifer (Q1)	0	-713.65
Natural recharge (Q2)	7553.8	0
Artificial recharge (Q3)	42.10	0
Recharge from leakage of the Public Water system and surface water use (Q4)	131.95	0
Return flow (Q5)	279.64	0
Losses to deep aquifers	0	-105.64
Total	8007.07	-819.28



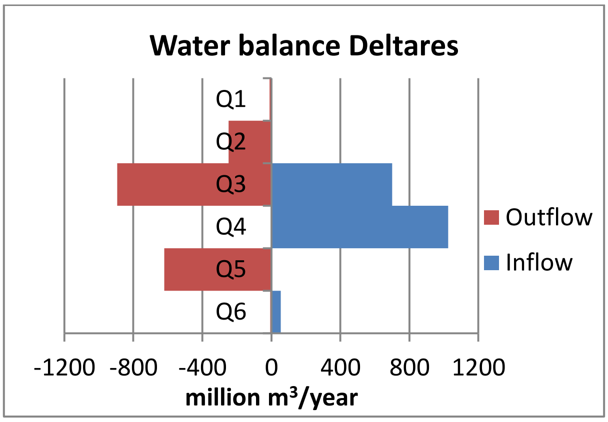
Abstraction from the shallow aquifer is a known definition, the other parts need some further explanation maybe. Recharge is in this model represented by direct natural recharge from infiltration of precipitation, artificial recharge presented by for instance precipitation deposition by rain pipes and percolation pits into the ground, and recharge from leakage of piped water and the use of surface water for industrial practices. Return flow is the water coming from underlying aquifers and losses to deep aquifers are to be explained by vertical movement of water from the shallow aquifer into deeper aquifers. One can see immediately that drainage (known and unknown) and the influence of rivers is not represented in the incomplete water balance in Table C-3

C.8.3 Deltares model

The Deltares model represents the Jakarta 1992 model. The fluxes are all larger than the values of the HAG 1980-85 model, except for the groundwater abstractions; these are almost 5 times smaller. The rivers are the major source of in and outflow. The other major inflow and outflow is represented resp. by recharge and by overland flow.

Table C-4. Water balance Deltares

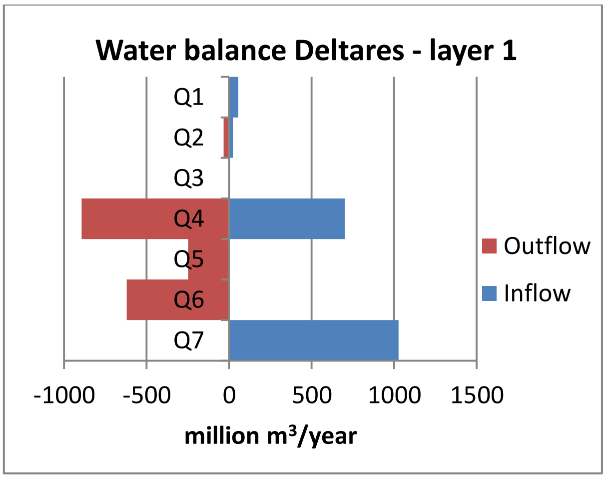
Flow	In (million m^3/year)	Out (million m^3/year)
Wells (Q1)	0	-10.95
Drainage (Q2)	0	-248.2
River (Q3)	700.8	-894.25
Recharge (Q4)	1025.65	0
Overland Flow (Q5)	0	-620.5
Boundary Flow (Q6)	54.75	-7.3
Total	1781.2	-1781.2



More interesting is to know the water balances of the different layers. Due to the combined size of the multiple water balances, they are presented in Appendix K. Special attention is given to layer 1, as it can be compared to the water balance for the shallow aquifer of the JWRMS model. The layer 1 water balance can be seen in Table C-4. The inequality of the end budgets is compensated by the inequality of budgets in layer 2, as can be seen in Appendix K.

Table C-5. Water balance of the first layer of the Deltares model

Layer 1	In (million m^3/year)	Out (million m^3/year)
Constant head (Q1)	54.75	-7.3
Flux lower face (Q2)	21.9	-32.85
Wells (Q3)	0	-3.65
Rivers (Q4)	700.8	-894.25
Drainage (Q5)	0	-248.2
Overland flow (Q6)	0	-620.5
Recharge (Q7)	1025.65	0
Total	1803.1	-1806.75



The recharge in Table C-3 (JWRMS model), which is in total 7727.85 million m^3/year, is almost 8 times the recharge of the Deltares model, though both models use the same map for recharge. The abstraction of the shallow aquifer in the JWRMS model is more than 70 times larger than the one in the iMOD model. Flow from the shallow aquifer to deeper aquifers is 3 times larger in the JWRMS balance and the flow from underlying aquifers differs by a factor 13. It can be concluded that the incomplete water balance of the shallow aquifer of the JWRMS model, and the water balance of the first layer in the Deltares model have nothing in common.

Appendix D: Comprehensive version of the sensitivity identification

Ramalingam (2001) made a model, in which he tried to estimate the availability of water in the Kallar river basin. For the computation of this model, MODFLOW software was used. He used the following parameters:

- Input
    - Rainfall recharge (83% of total recharge)
      The amount of precipitation which ends up in the soil. This calculated by subtracting evapotranspiration on the surface (26% of total discharge) and runoff from the precipitation.
    - River Bed Recharge (<1% of total recharge)
      The amount of water that infiltrates from the river through the riverbed into the underlying soil layer. The author could not really quantify this parameter and estimated it to be 20% of the rainfall recharge.
    - Irrigation Return Flow (16% of total recharge)
      The author estimated that 25% of irrigation water, which was extracted from underlying aquifers, returns to the groundwater.
    - Sub-surface Inflow (<1% of total recharge)
      Due to a hydraulic gradient, in this model also a sub-surface inflow from outside the watershed into is accounted for. This volume is the product of the transmissivity times the hydraulic gradient times the width of the aquifer.
- Output
    - Agricultural extraction (73% of total discharge)
      For irrigation groundwater is used. The amount of groundwater needed can be described by the area, evapotranspiration, the crop-coefficient, precipitation and infiltration.
    - Extraction for human and animal population (<1% of total discharge)
      For daily consumption it is estimated that per day 45 litres for humans is extracted and 25 for animals.
    - Sub-surface Outflow (<1% of total discharge)
      Same as sub-surface inflow, but then groundwater outflow out of the watershed.
- Characteristics
    - Transmissivities
    - Aquifer parameters
- Result
    - Computation of changes in storage
      With all inputs and outputs is per layer the net recharge or discharge computed and eventually the total net recharge/discharge per node in the model.

Punthakey and Joseph (2001) made a model for an aquifer system in Australia, with which water balances per layer could be presented. The model has a total of 3 layers. In this model also the groundwater movement between layers is accounted for. Other parameters they used were as follows:

- Input
    - Recharge (73% of total recharge)
      To different zones were different factors for recharge assigned, that is low, medium and high recharge.

- River (21% of total recharge)
  Inflow from the river to the aquifer is dependent of the difference in water head between the river and the aquifer (here: inflow when head in aquifer is lower than river head) and of the conductance of the river bed.
- Boundary Inflow (6% of total recharge)
  Subsurface inflow into study area from outside the study area.

- Output
  - Evapotranspiration (19% of total discharge)
    Dependent of land use, critical depth and topography and of water heads in cells in the model.
  - Wells (37 % of total discharge)
    Abstraction points with a more or less continuous outflow from the model.
  - River (39% of total discharge)
    Same as River as input parameter, only now an output if the water head of the aquifer rises above the water head in the river.
  - Boundary Outflow (5% of total discharge)
    Subsurface outflow from the study area to outside the study area.
- Characteristics
  - Aquifer properties
- Result
  - Preliminary water balances for each layer.

De Vries (2015) schematised the shallow aquifer of Jakarta in a model, based on a literature study and a survey she did. The following parameters were accounted for in her model:

- Input
  - Rain infiltration
    It was estimated that 10% of the precipitation infiltrates into the soil. This percentage was varied between 5% and 24%.
  - Leakage piped water network
    In Jakarta a water distribution network is present, but it is estimated that the leakage of water into the soil is between 40% and 60% of the losses in the network.
  - Septic tank infiltration
    Apart from being connected to the sewer system, households can also use septic tank to dispose waste. It is estimated that 72% of the population of Jakarta uses a septic tank. The infiltration from septic tanks is then estimated to be between 80% and 120% of the daily water consumption of this part of the population.
- Output
  - Groundwater abstraction
    The author argues that mostly households extract water from the shallow aquifer. It is estimated that 67% of the population uses groundwater to fulfil the need of an estimated 95,4 L per person per day.
  - Percolation to confined aquifers and surface water
    The author estimates that overall from percolation 25% of the water ends up in surface water and 75% in aquifers underlying the shallow aquifer. The percolation volume however is in the range of 15% to 25% of the total precipitation that infiltrates into the shallow aquifer.
- Result
  - Water balance for the shallow aquifer of Jakarta.

Senthil Kumar and Elango (2001) made a numerical model to schematise the groundwater flow in an unconfined aquifer system in an Indian river basin. They used MODLFLOW software to compute runs. The model formulation was as follows:

- Input
    - Boundary Inflow (0% of total inflow)
      No flow boundaries as in at the northern, southern and western boundaries of the study area the aquifer is only 1 m thick. In the east a constant head boundary was considered, since this part of the study area was bounded by the Bay of Bengal.
    - Recharge
      Dependent of the precipitation per month
    - Return flow from irrigation
    - Infiltration from reservoir
- Output
    - Groundwater abstraction
- Characteristics
    - Hydraulic conductivity
    - Thickness of layers
    - Transmissivity
    - Specific yield
- Result
    - Transient state condition groundwater flow schematisation

Balasubramanian (2001) made a summary about hydrogeological models and their requirements. He made a distinction between models for analysing groundwater occurrence and flow, for analysing dispersal, mobility and distribution of solutes, for analysing mechanisms of rock-water geochemical interactions, and for analysing salinity intrusions. The mentioned parameters describing input, output and characteristics of groundwater occurrence and flow models, were as follows:

- Boundaries
- Aquifer types and thicknesses
- Initial water heads
- Transmissivity
- Hydraulic conductance
- Specific yield
- Storativity
- Locations and volumes of recharge and discharge

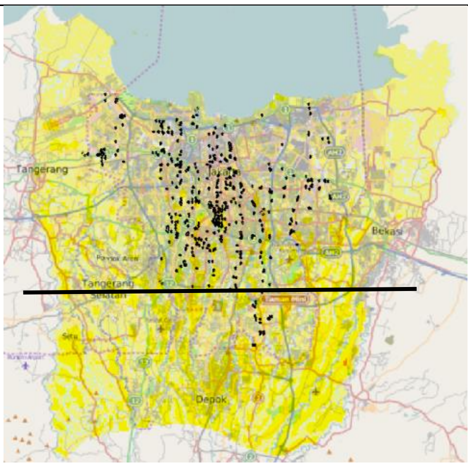
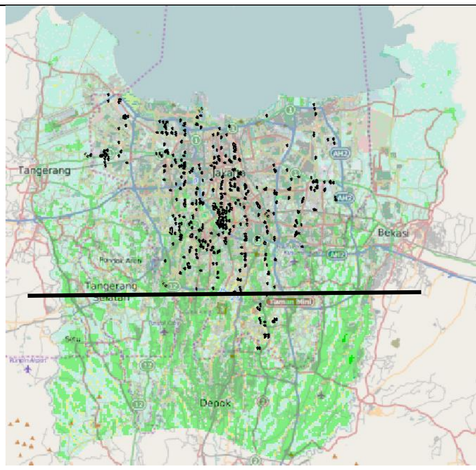
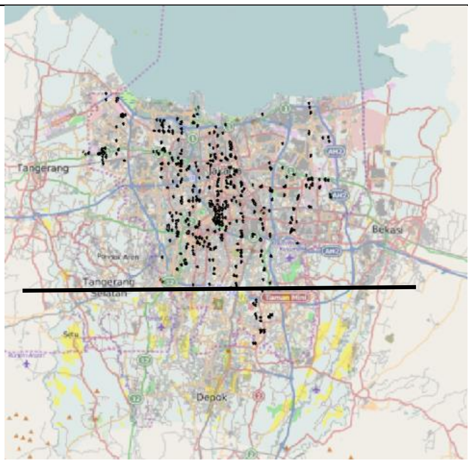
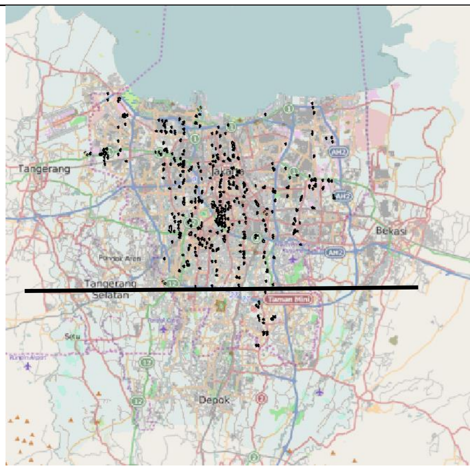
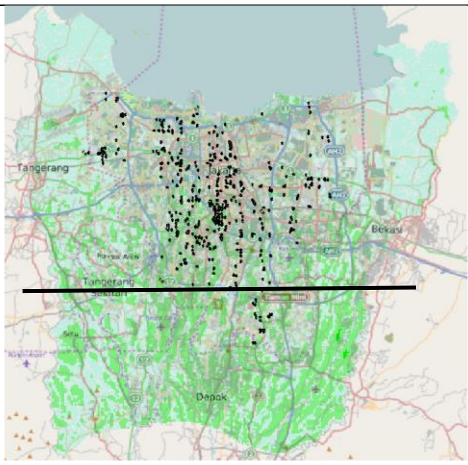
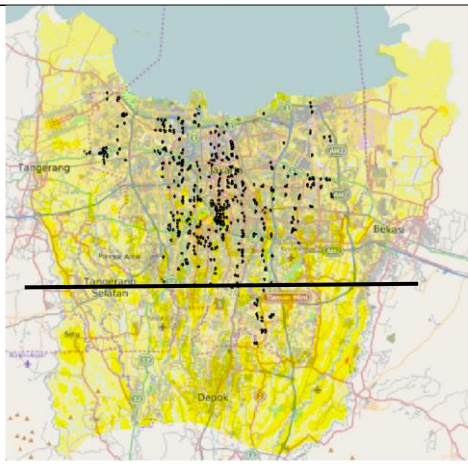
Ravi et al. (2001) schematised an aquifer system into a two layer aquifer system. For the computation they used MODFLOW software. The used the following parameters for the model design:

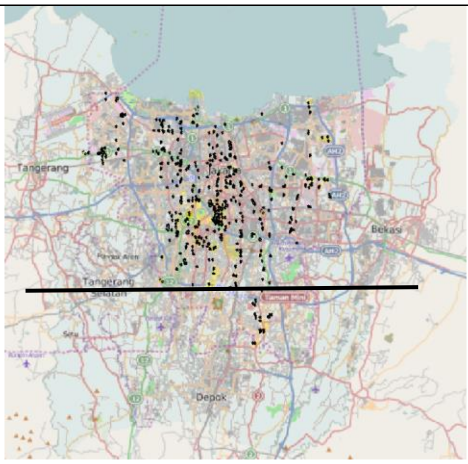
- Input
    - Subsurface inflow from the west
    - Infiltration recharge (15% of total precipitation)
- Output
    - Subsurface outflow in the east along the sea
    - Wells
- Characteristics
    - Thicknesses of aquifers and aquitards

- Transverse flows determined by differential heads and aquitard conductivity and thickness
    - Hydraulic conductivity
    - Storativity
    - Initial water heads
- Result
    - Water balance for determining a sustained development of groundwater resources

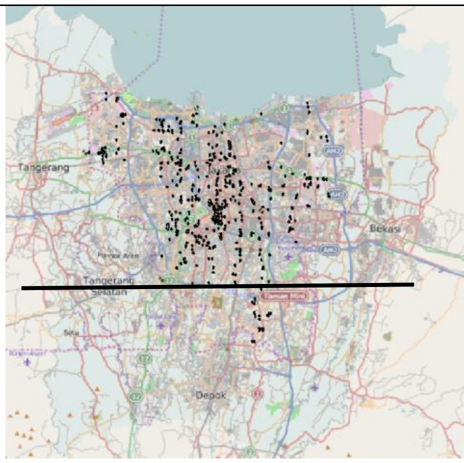
Appendix E: Sensitivity of water heads to parameter adjustment

Layer 1

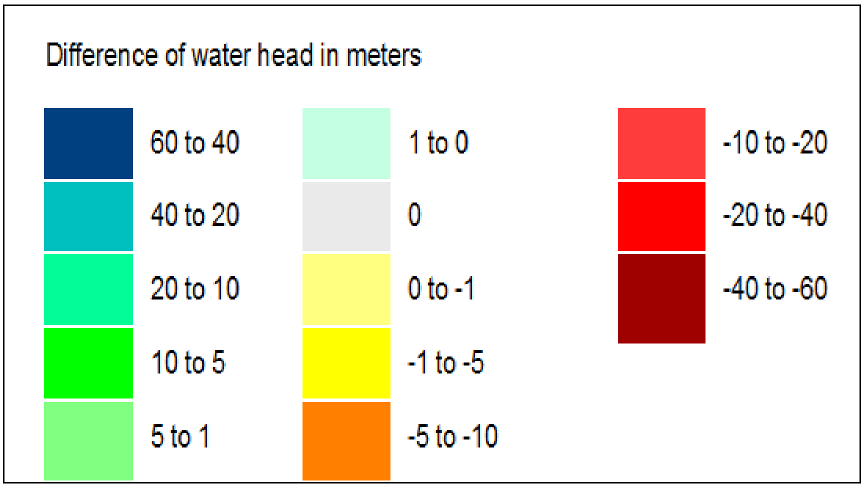
Factor 2	Factor 0.5
 Layer 1 - horizontal hydraulic conductivity (KHV) factor 2	 Layer 1 - horizontal hydraulic conductivity (KHV) factor 0.5
 Layer 1 - vertical hydraulic conductivity (KVA) factor 2	 Layer 1 - vertical hydraulic conductivity (KVA) factor 0.5
 Layer 1 - recharge (RCH) – factor 2	 Layer 1 - recharge (RCH) factor 0.5



Layer 1 - abstractions from wells (WEL) factor 2

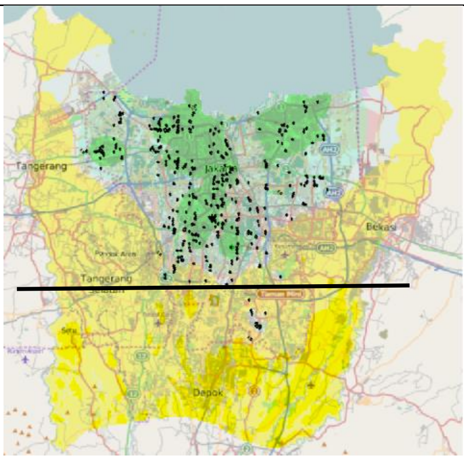
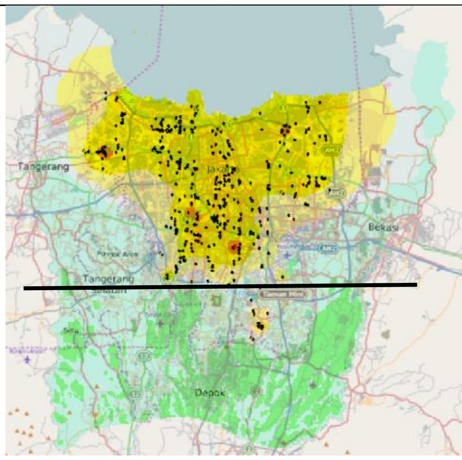
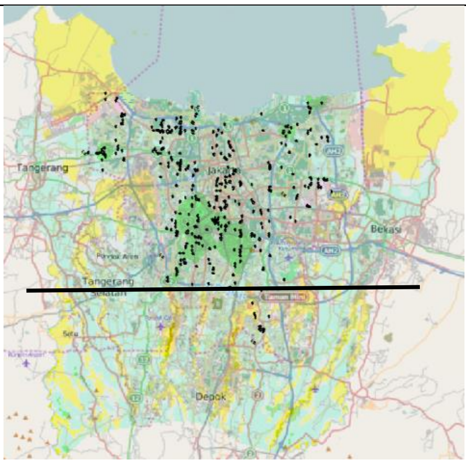
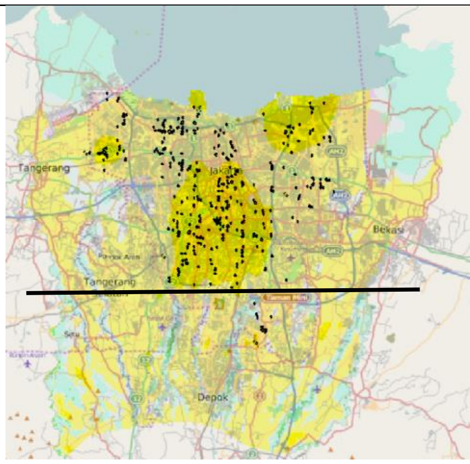
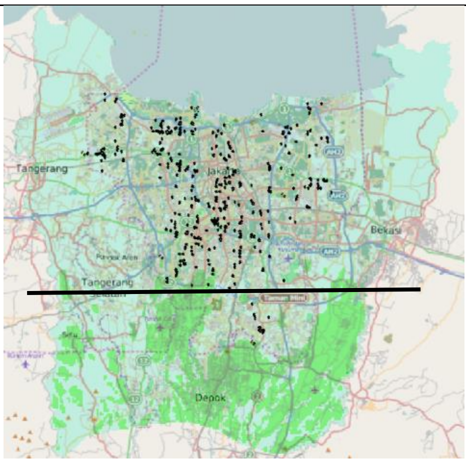
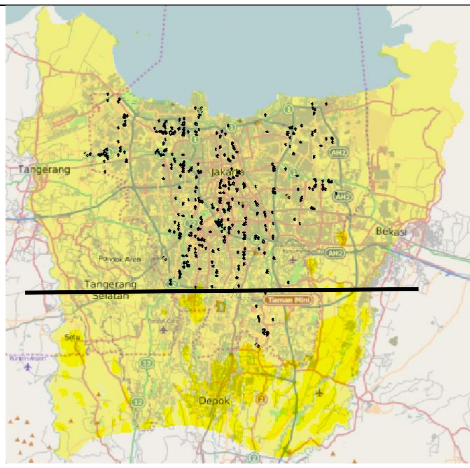


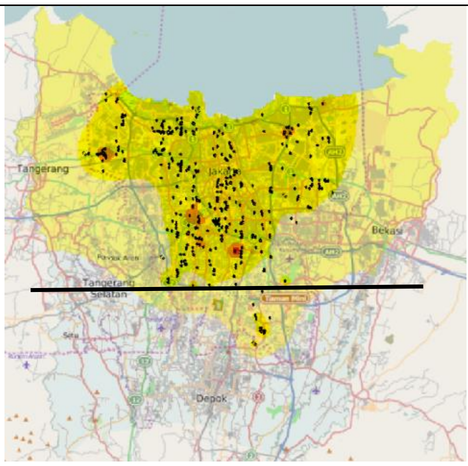
Layer 1 - abstractions from wells (WEL) factor 0.5



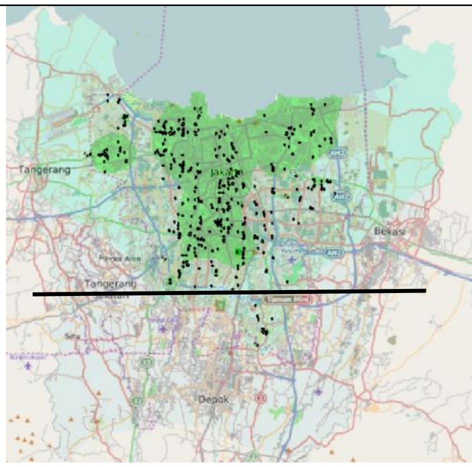
In the maps the difference in water head in meters (as calculated with the equation given in section 4.3) is given for layer 1 per parameter adjustment. In the maps the black dots are the wells and the black line the division between the northern and southern area of the study area.

Layer 2

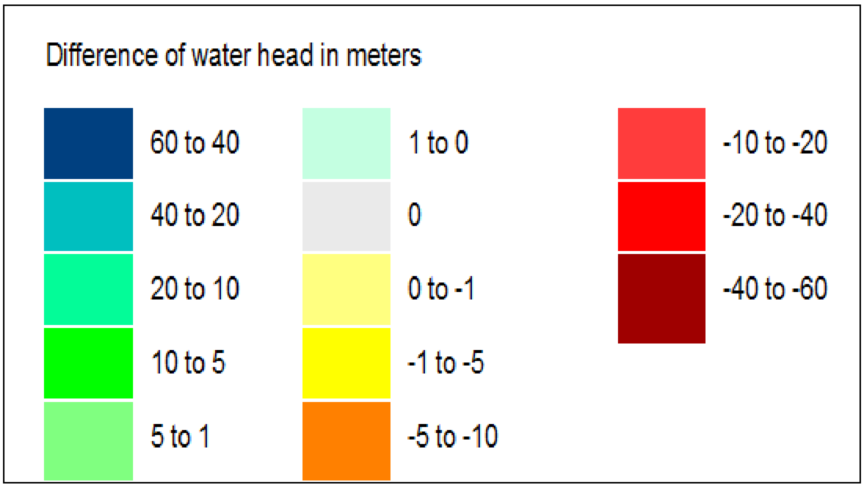
Factor 2	**Factor 0.5**
 Layer 2 - horizontal hydraulic conductivity (KHV) factor 2	 Layer 2 - horizontal hydraulic conductivity (KHV) factor 0.5
 Layer 2 - vertical hydraulic conductivity (KVA) factor 2	 Layer 2 - vertical hydraulic conductivity (KVA) factor 0.5
 Layer 2 - recharge (RCH) factor 2	 Layer 2 - recharge (RCH) factor 0.5



Layer 2 - abstractions from wells (WEL) factor 2

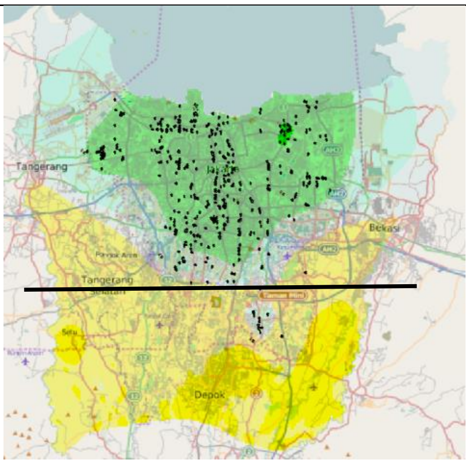
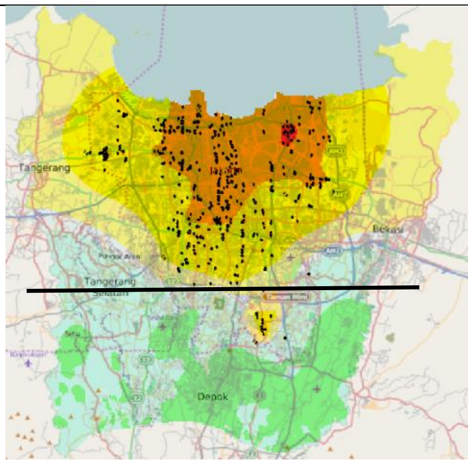
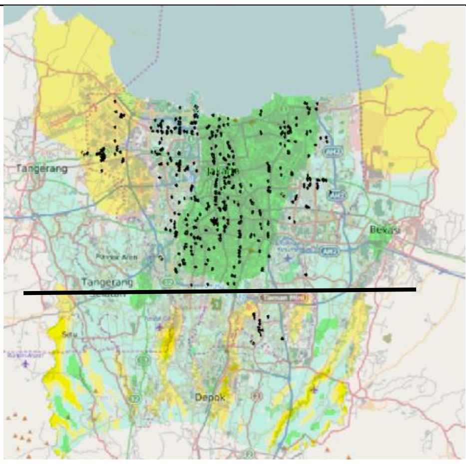
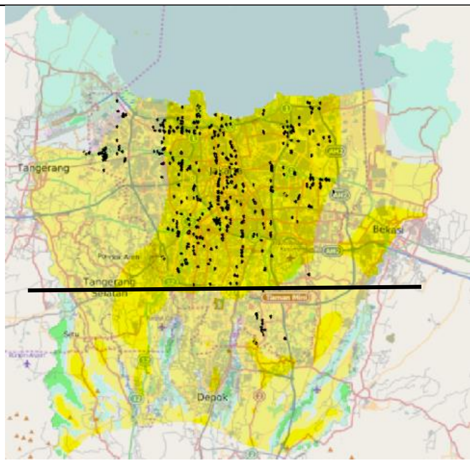
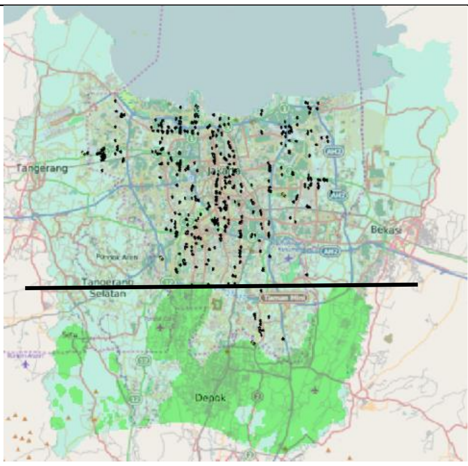
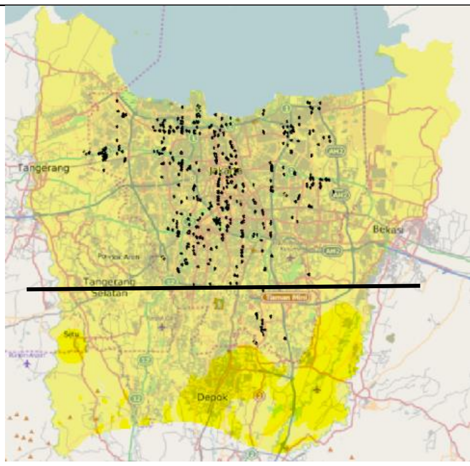


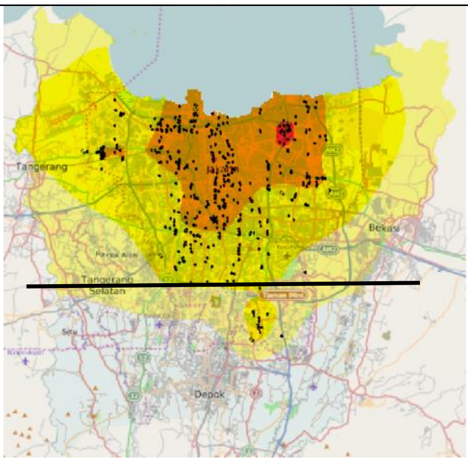
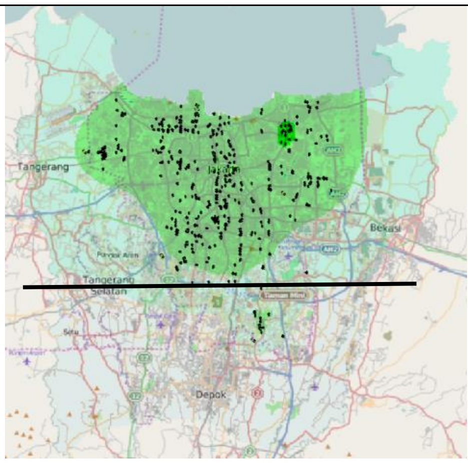
Layer 2 - abstractions from wells (WEL) factor 0.5

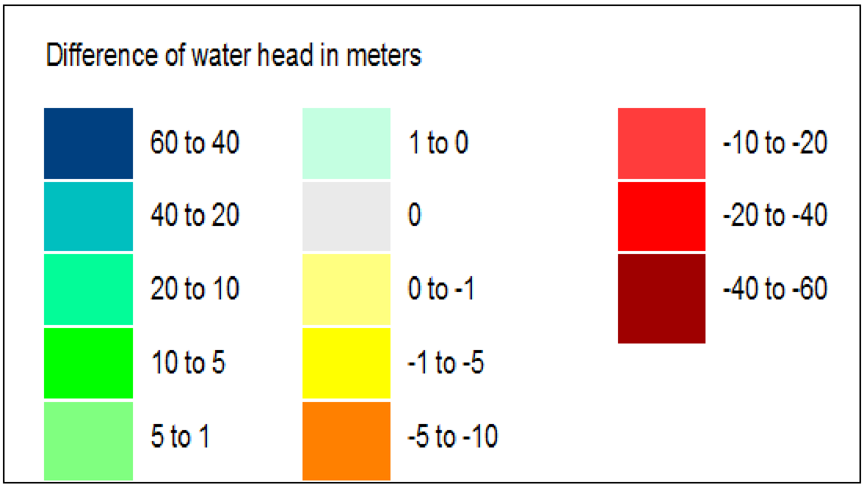


In the maps the difference in water head in meters (as calculated with the equation given in section 4.3) is given for layer 2 per parameter adjustment. In the maps the black dots are the wells and the black line the division between the northern and southern area of the study area.

Layer 3

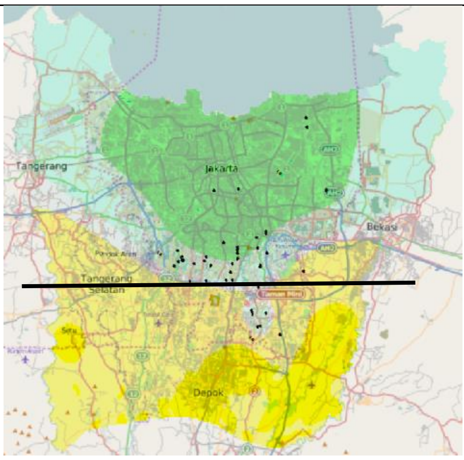
Factor 2	Factor 0.5
 Layer 3 - horizontal hydraulic conductivity (KHV) factor 2	 Layer 3 - horizontal hydraulic conductivity (KHV) factor 0.5
 Layer 3 - vertical hydraulic conductivity (KVA) factor 2	 Layer 3 - vertical hydraulic conductivity (KVA) factor 0.5
 Layer 3 - recharge (RCH) factor 2	 Layer 3 - recharge (RCH) factor 0.5

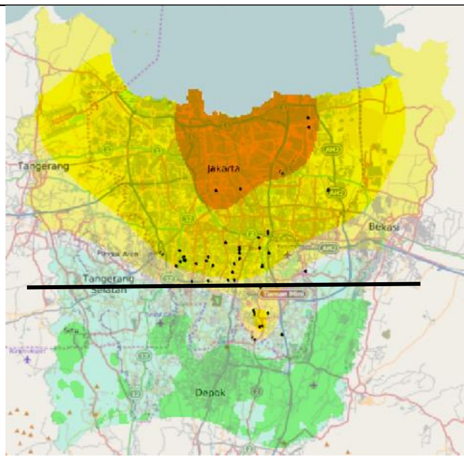
 Layer 3 - abstractions from wells (WEL) factor 2	 Layer 3 - abstractions from wells (WEL) factor 0.5

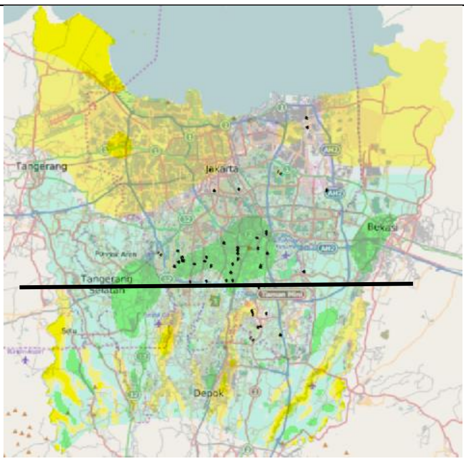


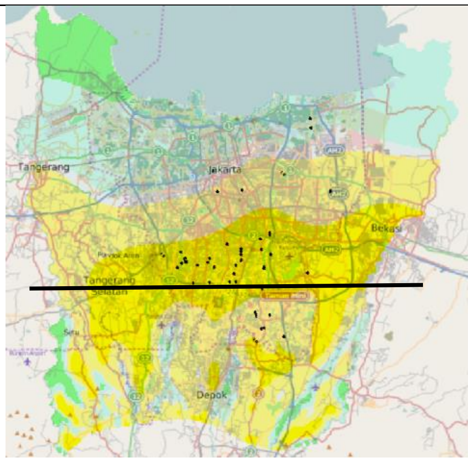
In the maps the difference in water head in meters (as calculated with the equation given in section 4.3) is given for layer 3 per parameter adjustment. In the maps the black dots are the wells and the black line the division between the northern and southern area of the study area.

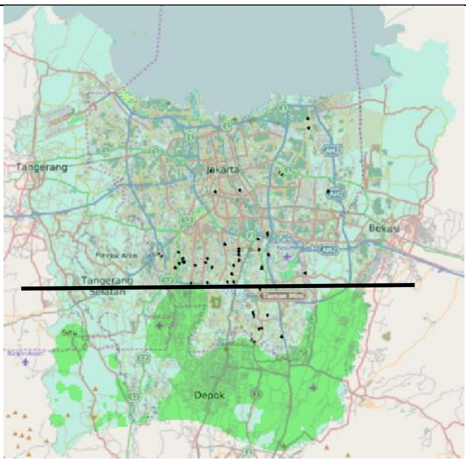
Layer 4

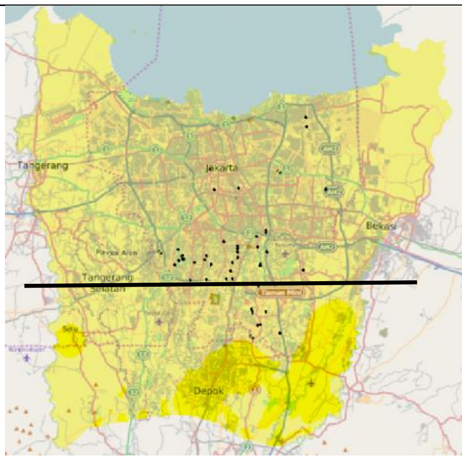
<table>
<tr><th>Factor 2</th><th>Factor 0.5</th></tr>
<tr><td>


Layer 4 - horizontal hydraulic conductivity (KHV)
factor 2
</td><td>


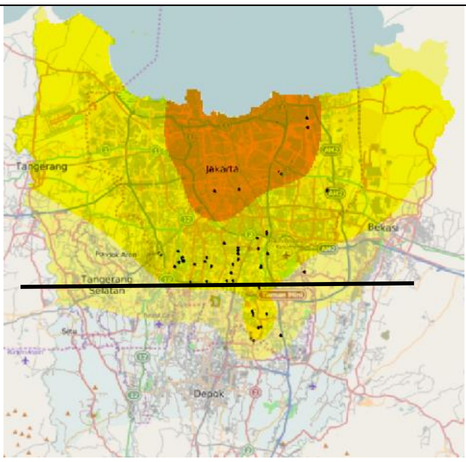
Layer 4 - horizontal hydraulic conductivity (KHV)
factor 0.5
</td></tr>
<tr><td>


Layer 4 - vertical hydraulic conductivity (KVA)
factor 2
</td><td>


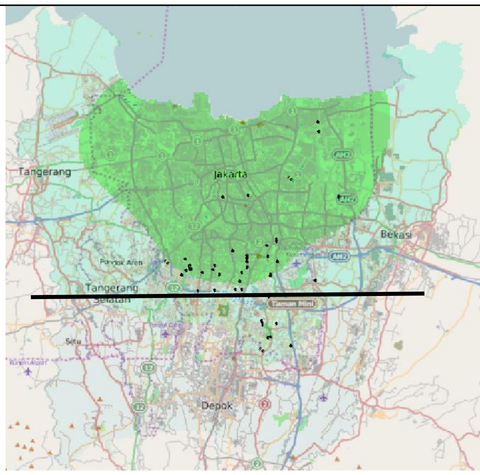
Layer 4 - vertical hydraulic conductivity (KVA)
factor 0.5
</td></tr>
<tr><td>


Layer 4 - recharge (RCH)
factor 2
</td><td>


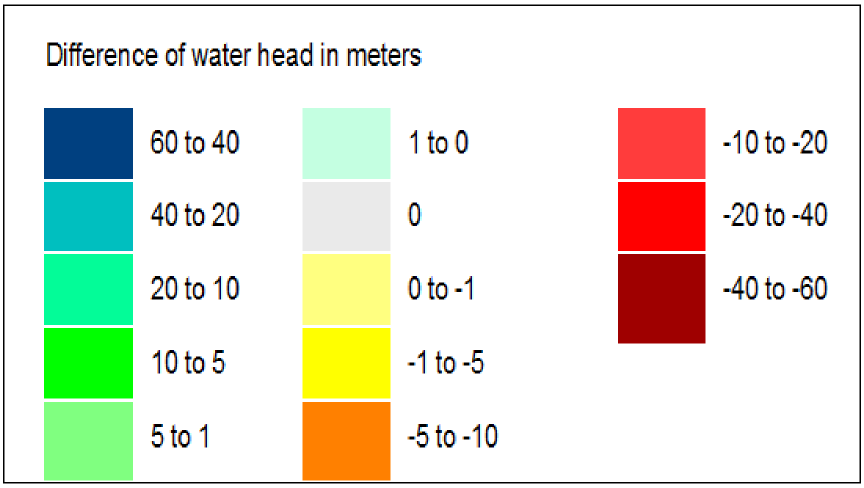
Layer 4 - recharge (RCH)
factor 0.5
</td></tr>
</table>



Layer 4 - abstractions from wells (WEL) factor 2



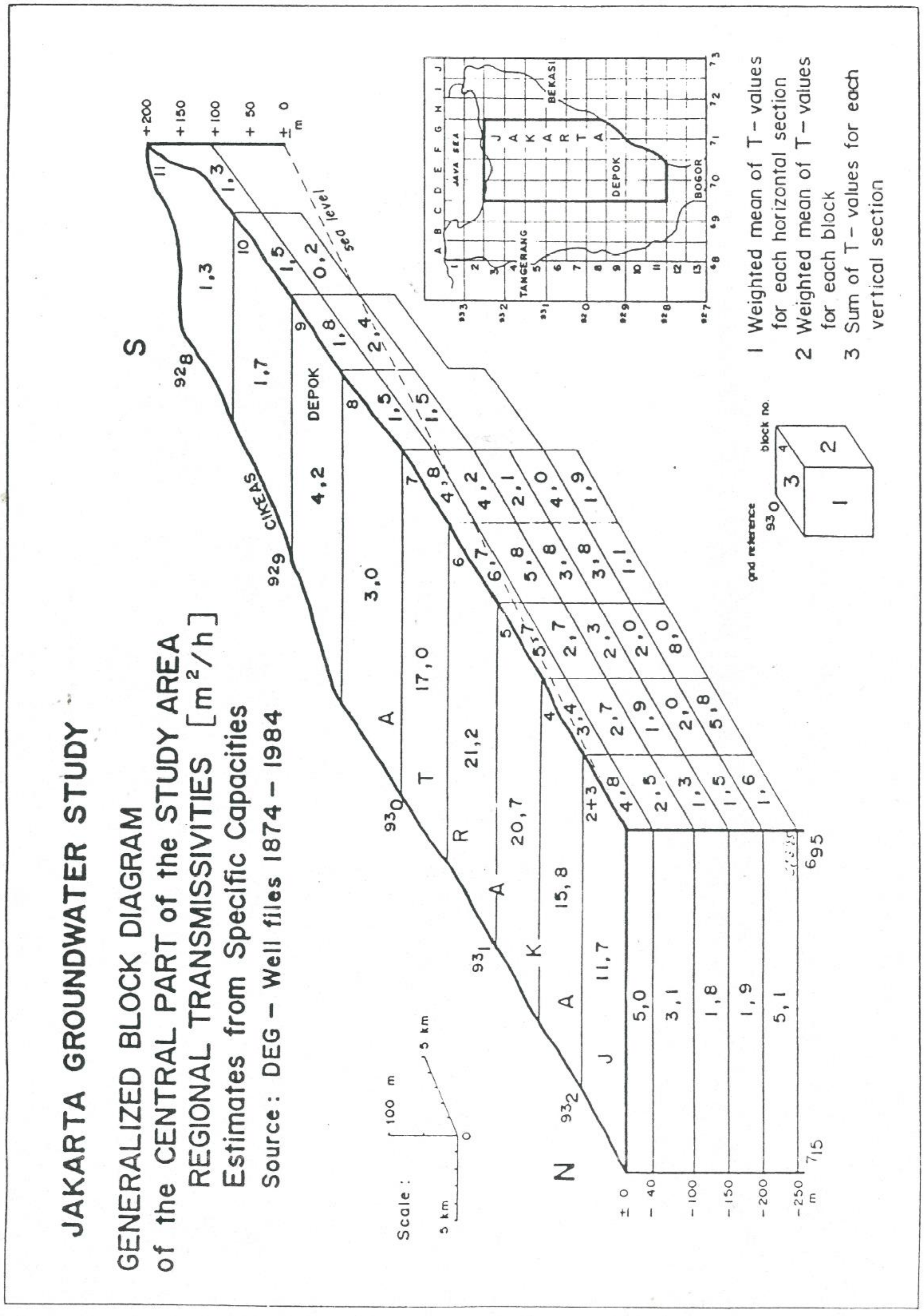
Layer 4 - abstractions from wells (WEL) factor 0.5



In the maps the difference in water head in meters (as calculated with the equation given in section 4.3) is given for layer 4 per parameter adjustment. In the maps the black dots are the wells and the black line the division between the northern and southern area of the study area.

Appendix F: Synoptical transmissivity overview of the HAG model

This overview is from the work of (Erlangga, Soefner, & Zaepke, 1985)



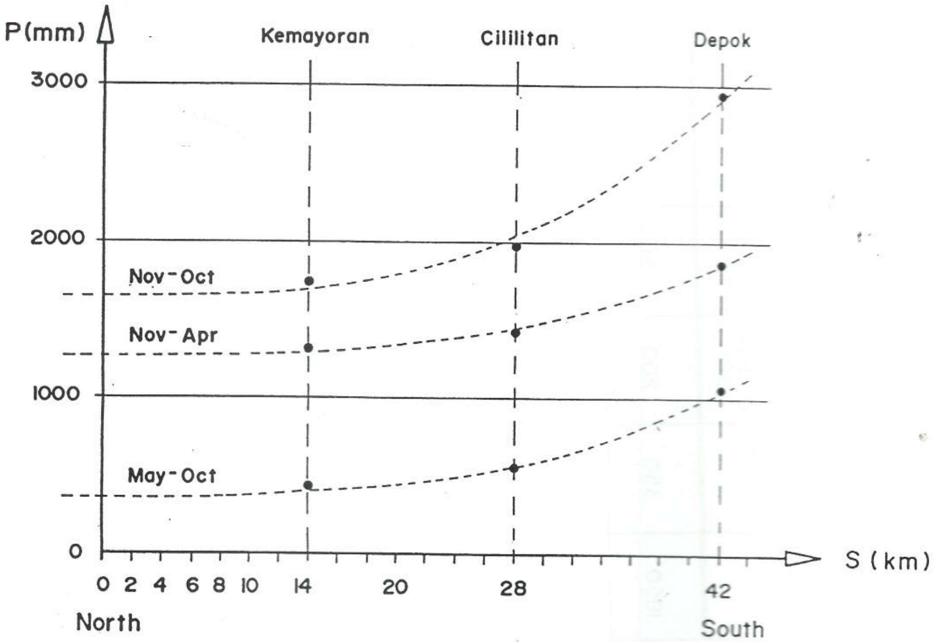
Appendix G: Rainfall and recharge in the HAG model

The equations as used by (Soefner et al., 1986)

Average Rainfall P (mm) 1951 - 82

	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov-Apr	May-Oct	Nov-Oct
Kemayoran	90	190	440	300	200	100	95	80	60	65	50	80	1320	430	1750
Cililitan	180	220	360	290	210	160	130	90	70	80	80	110	1420	560	1980
Depok	270	280	390	300	300	340	240	160	110	140	190	220	1880	1060	2940

(see also working paper HAG 75)



Rainfall - Function for Jakarta - Groundwater - Model

Nov - Oct : $P = 1.50 \cdot 10^{-2} \cdot S^3 + 8.50 \cdot 10^{-2} \cdot S^2 + 1650$

Nov - Apr : $P = 6.75 \cdot 10^{-3} \cdot S^3 + 5.03 \cdot 10^{-2} \cdot S^2 + 1270$

May - Oct : $P = 8.75 \cdot 10^{-3} \cdot S^3 + 3.92 \cdot 10^{-3} \cdot S^2 + 380$

Appendix H: Recharge in the JWRMS model

The two formulae used were (JWRMS, 1994):

$$R_{perv} = (1 - f_{impv}) + (P * (1 - k_{dsro}) - E_{act})$$

$$R_{impv} = f_{impv} * k_{impv} * (P - Ea_{impv})$$

Where:

R_{impv} = recharge of rainwater falling on 'impervious' surface like roofs and pavements

R_{perv} = recharge of rainwater falling on 'pervious' surface like gardens, bare soil, gravel and broken stone pavements

f_{impv} = percentage 'impervious' surface in an area (related to population densities and commercial activities). See table III.1

P = rainfall

k_{dsro} = percentage of direct surface run-off from pervious soil (set at 10%)

k_{impv} = percentage of net rain falling on impervious surfaces, which infiltrates in the ground. See table III.2

Ea_{impv} = actual evapotranspiration from impervious surface

Ea_{perv} = actual evapotranspiration from pervious areas with vegetation

Tabel V-1. Estimated relation between population densities and percentage impervious surface

Population density in people per ha	<50	50 – 100	100 – 150	150 – 200	200 – 250	250 – 300	300 – 350	350 – 400	400 – 500	>500
Percentage impervious surface	10%	25%	40%	50%	57%	65%	70%	75%	80%	85%

A correction is made for those kecamatans where industrial and commercial activities are more intensive than would be expected based on the population densities. Two classes were used:

Moderate: Density corrected by adding 50 people per ha

High : Density corrected by adding 100 people per ha

Table V-2. Percentage of run-off from impervious areas infiltrating according to drainage system infiltration class

Drainage system infiltration class	1	2	3	4
Percentage of run-off infiltrating	20%	25%	30%	40%

Appendix I: HAG wells and abstraction compared to BPLHD data

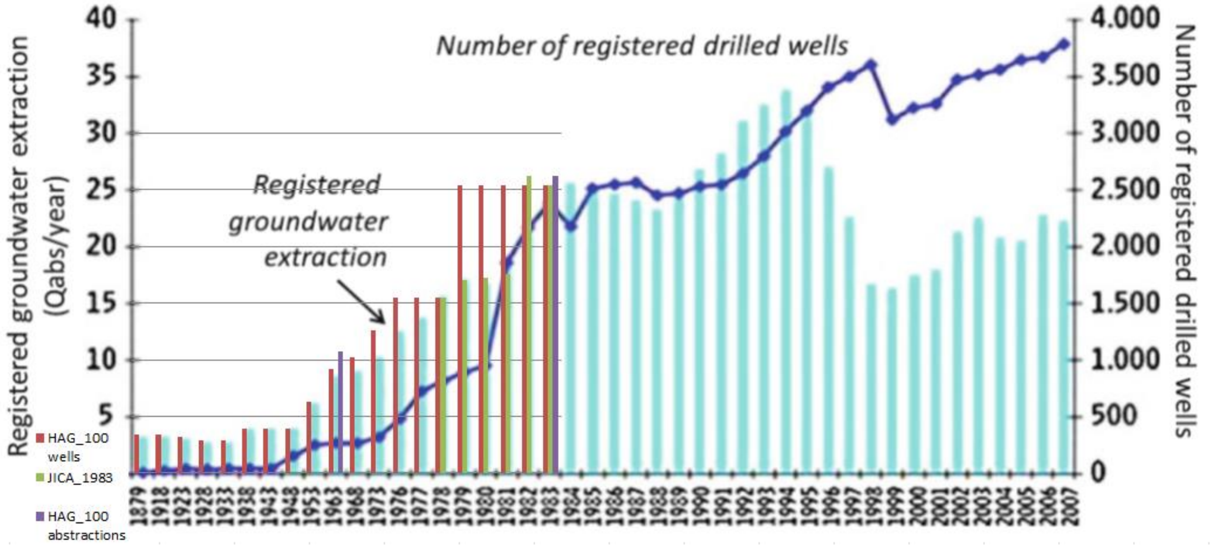


Figure H-1. Djaeni (1985) and JICA (1983) abstractions compared to PAM Jaya registered groundwater abstraction.

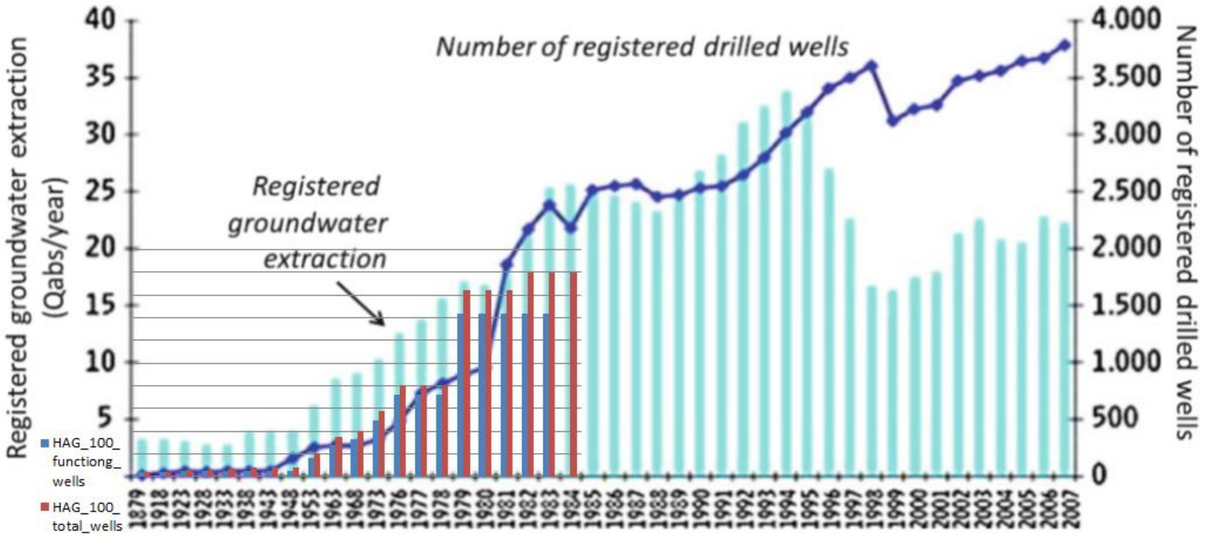


Figure H-2. Number of wells from Djaeni (1985) compared to registered at PAM Jaya.

Appendix J: Abstraction data from the JWRMS

Table I-1. Abstraction found at field survey and abstraction found in tariff lists of registered wells. Adapted from JWRMS (1994)

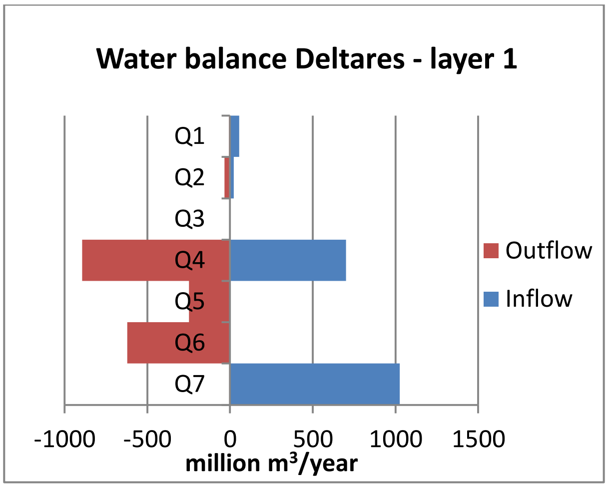
Wilayah	Registered abstraction		Abstraction found during field survey		Multiplier
	Number of wells	Abstraction (m^3/month)	Number of wells	Abstraction (m^3/month)	
DKI Jakarta	247	479.472	202	605.733	1.26
Jakarta Selatan	33	90.538	20	59.050	0.65
Jakarta Timur	83	172.008	70	192.591	1.12
Jakarta Pusat	30	97.950	26	146.610	1.50
Jakarta Barat	35	49.894	32	96200	1.93
Jakarta Utara	66	69.082	54	111.282	1.61

Table I-2. Abstractions found at wells not registered by PAM Jaya and wells registered by PAM Jaya and the multiplier between real registered and real total abstractions. Adapted from JWRMS (1994)

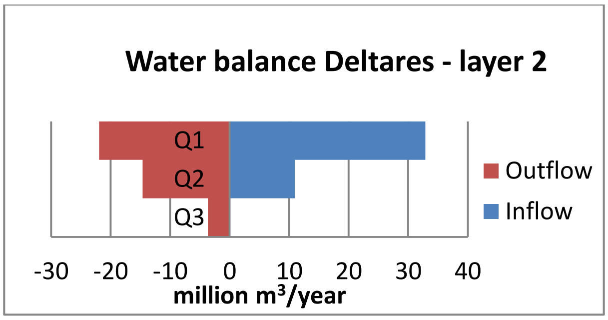
Wilayah	Well not registered at PAM Jaya		Wells registered at PAM Jaya		Total field survey		Multiplier
	Number of wells	Abstraction (m^3/month)	Number of wells	Abstraction (m^3/month)	Number of wells	Abstraction (m^3/month)	
DKI Jakarta	182	464.903	202	605.733	384	1070.636	1.77
Jakarta Selatan	22	57.925	20	59.050	42	116.975	1.98
Jakarta Timur	46	119.086	70	192.591	116	311.677	1.62
Jakarta Pusat	21	70.500	26	146.610	47	217.110	1.48
Jakarta Barat	51	138.712	32	96200	83	234.912	2.44
Jakarta Utara	42	78.680	54	111.282	96	189.962	1.71

Appendix K: Water balances per layer from the Deltares model

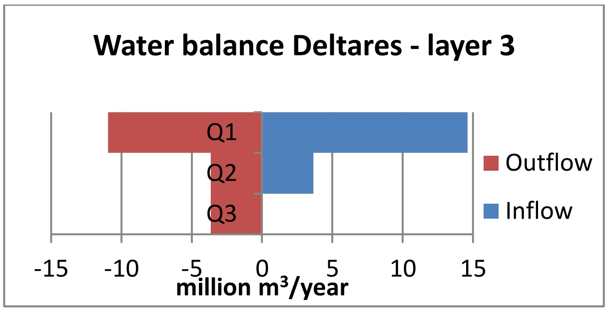
Layer 1	In (million m^3/year)	Out (million m^3/year)	
Constant head (Q1)	54.75	-7.3	
Flux lower face (Q2)	21.9	-32.85	
Wells (Q3)	0	-3.65	
Rivers (Q4)	700.8	-894.25	
Drainage (Q5)	0	-248.2	
Overland flow (Q6)	0	-620.5	
Recharge (Q7)	1025.65	0	
Total	1803.1	-1806.75	-3.65



Layer 2	In (million m^3/year)	Out (million m^3/year)	
Flux upper face (Q1)	32.85	-21.9	
Flux lower face (Q2)	10.95	-14.6	
Wells (Q3)	0	-3.65	
Total	43.8	-40.15	3.65



Layer 3	In (million m^3/year)	Out (million m^3/year)	
Flux upper face (Q1)	14.6	-10.95	
Flux lower face (Q2)	3.65	-3.65	
Wells (Q3)	0	-3.65	
Total	18.25	-18.25	0



Layer 4	In (million m^3/year)	Out (million m^3/year)	
Flux upper face (Q1)	3.65	-3.65	
Flux lower face (Q2)	0	0	
Wells (Q3)	0	0	
Total	3.65	-3.65	0