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Modeling of groundwater flow of the Hagadrag aquifer to monitor drinking water supply for the Bø municipality

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This thesis is worth 60 study points

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Abstract

Groundwater flow model is a numerical representation of the complex hydrological system into simple graphical form for simulation and prediction. The purpose of developing groundwater flow models vary from study to study and follows a sequential modeling approach. This study was designed to develop a groundwater flow model for Hagadrag aquifer situated in Bø and Seljord municipalities of the Telemark County in the southeastern part of Norway. The aim of the model development was to determine the flow pattern in the aquifer and capture zones of the pumping wells, thereby monitoring the groundwater for any possible contamination source. The numerical model was developed in Processing Modflow (PMWIN) using ArcMap as pre and post processor. The data required for the model development were extracted from national map data and fieldwork from previous studies. The use of ArcMap as a GIS tool to process the data for modeling and visualizing the model developed in PMWIN has been justified in this study. The model was calibrated using manual trial-and-error calibration. The calibrated parameters included riverbed conductance, precipitation and infiltration from injection wells. Among these, riverbed conductance was the most sensitive parameter. The calibration of the model was not only focused on quantitative measure of RMSE, but also on the appropriateness of the estimated parameter values that comply with the conceptual model. The simulations show that the location of a well in accordance to river bends and distance from river determines the flow pattern. The Bø river and Herretjønn are the major surface water resources infiltrating into the Hagadrag aquifer. However, the volume of water infiltrated from these surface water resources depend on the precipitation and volume of water extracted from the pumping wells. The findings from this study suggest that any contamination to the Bø river upstream and Herretjønn can be a big threat to the aquifer, thereby requiring continuous monitoring of these surface water resources.

Keywords: *Hagadrag aquifer, groundwater, numerical model, PMWIN, ArcMap.*

Abbreviations and acronyms

BCF	Block Centered Flow
BP	Before Present
CO_2	Carbon dioxide
d	Day
da	Decare
DO	Dissolved oxygen
FKB	Felles kart database
GHB	General Head Boundary
GIS	Geographical Information System
km^2	Square kilometer
l	Liter
l/s	Liter per second
LPF	Layer-Property Flow
m	Meter
m^3/d	Cubic meter per day
m^3/hr	Cubic meter per hour
MAE	Mean absolute error
m a.s.l	Meters above sea level
ME	Mean error
mm/yr	Millimeter per year
N/A	Not applicable
NEVINA	Nedbørfelt og vannføringsindeksanalyse
NVE	Norges vassdrags- og energidirektorat
PEST	Parameter Estimation

PMWIN	Processing Modflow for Windows
RMSE	Root mean squared error
s	Second
USGS	United States Geological Survey
WHO	World Health Organization

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1 Introduction

1.1 Background

Water is vital for all living organisms. Around 70.9% of our planet is surrounded by water. Water is useful for drinking purposes, irrigation as well as industrial purposes. Out of all these uses of water, water used for drinking requires the utmost attention. To fulfill all these needs, groundwater is used in excessive quantity since groundwater is the world's largest freshwater resources.

Groundwater accounts for 95% of the total freshwater resources on the earth. As the name suggests, groundwater is found in the ground beneath us usually filling the pores and cracks in the soil sediments and mountains respectively. The groundwater resources in Norway are found in soil sediments and are relatively smaller with an exception of the Gardermoen aquifer (NGU, 2015b). The quality, amount and depth of the groundwater depends on the climatic and geological condition of the soil sediments. The soil layer of the aquifer in Norway mostly consists of permeable sand or gravel. The groundwater level varies with the season in Norway, and depends on the location of the aquifer as the climatic condition varies widely across the country. The climatic conditions include precipitation and evaporation that determine the amount of water available for infiltration into the soil layer, whereas the geological properties of the soil sediments determine whether the surface water can infiltrate into the ground to fill the groundwater reservoir. In the time between the infiltration of water from precipitation and other surface water resources until it reaches the groundwater reservoir, the infiltrated water undergoes a series of chemical exchange process and natural cleaning for pathogenic microbes. This natural cleaning and chemical exchange process results in the quality difference between groundwater and surface water.

The national standard for drinking water in Norway has been established by the Ministry of Health and Care Services (Helse- og omsorgsdepartementet, 2016). Water used for drinking purpose must be of good quality and safe in order to prevent any serious health hazards. The quality of drinking water is affected by several physical, chemical and biological parameters with their own standards and limits to be considered safe for drinking. The World Health Organization (WHO) has presented the limit for these physical, chemical and biological parameters that determine the quality of safe drinking water (WHO, 2011). A good quality safe drinking water should be pure, clean and clear in visuality, free from any chemical and biological contaminants and meet the standard set by WHO or the national guidelines. The sensory and physical parameters include color, taste, odor, conductivity and turbidity. The chemical parameters include pH and various inorganic or organic elements and compounds whereas the biological parameter includes microorganisms.

The groundwater in Norway has fewer organic matter but has comparatively higher pH, electrical conductivity and hardness than the surface water (NGU, 2015b). Despite the fact that the groundwater is more protected from contamination than the surface water, it cannot be neglected that human activities and natural processes can still deteriorate the quality of groundwater (NGU, 2015a). Therefore, continuous monitoring and quality control of the groundwater resources needs to be conducted. The Geological Survey of Norway[1] (NGU) is the governmental body in Norway responsible for investigation of groundwater and well drilling, which in co-operation with the Norwegian Water Resources and Energy Directorate[2] (NVE) monitors the nationwide program for quantity and quality of groundwater.

One of the methods to monitor groundwater quality is to use groundwater flow model. The groundwater flow model simulates the behavior of the aquifer in response to planned operations like pumping and recharging in the form of changes in water levels, quality or land subsidence (Bear & Verruijt, 2012). Groundwater flow model is a simplified version of the real groundwater system that helps to estimate the rate and direction of groundwater flow through aquifer (Khadri & Pande, 2016), and thus considered an appropriate tool to assess the effect of human activities on groundwater dynamics (Dawoud et al., 2005; Mao et al., 2005; Mylopoulos et al., 2007; Xu et al., 2011). This thesis presents a groundwater flow model of Hagadrag aquifer situated in Bø and Seljord municipalities of the Telemark County in the southeastern part of Norway. The aquifer is the drinking water supply for the Bø municipality. The Hagadrag aquifer is a combination

[1] www.ngu.no

[2] www.nve.no

of confined and unconfined aquifer. The surface water resources around the aquifer are Bø river, Lake Seljord, Hønsåa and two large kettle holes namely Kupatjønn and Herretjønn. The unconfined layer may have interconnection to the surface water i.e. water table is in good hydrologic connection with the surface water bodies (York et al., 2002). Thus, the presence of contamination in any of these resources can affect the quality of groundwater in the Hagadrag aquifer. In addition, agricultural land, residential areas and camping place surround the areas around the pumping wells in the aquifer region, and thus considered vulnerable to contamination by anthropogenic activities.

1.2 Problem statement and purpose

The area around Hagadrag aquifer are used for different purposes like gravel pits, recreation, agriculture, high traffic road (Rv.36) etc. The pumping wells are either near to gravel pits or near to the road and also have impact from hiking trails. These multiple uses of the surrounding area may lead to over exploitation of the groundwater and pose threats to the drinking water quality.

The anthropogenic activities near the Hagadrag aquifer and drinking water supply demand a proper monitoring to avoid any unwanted contamination. The use of de-icing salt on the road during winter season has been considered as the major threat for chloride contamination to the Hagadrag aquifer. The presence of high chloride and manganese concentration in Herretjønn has indicated that Herretjønn can be a major suspect of contamination source. In order to track these possible contamination transport pathway it is necessary to understand the pattern of groundwater flow in the aquifer, thereby indicating a need of an updated groundwater flow model of the Hagadrag aquifer.

Therefore, the aim of this study is to develop a groundwater flow model for Hagadrag aquifer in order to identify the capture zones of pumping wells. The model developed in this study is expected to give detail information of groundwater flow pattern inside the Hagadrag aquifer and capture zones of the pumping wells, especially the last well 4 (Klempe, 2009). This flow pattern can further help to monitor the groundwater quality that can be easily effected by various contaminants if any might occur in future.

2 Literature review

2.1 Groundwater flow and contamination transport

The quality of groundwater is comparatively better than the surface water, since the groundwater is less prone to pathogenic microbes as it undergoes extensive cleaning and change in chemical composition during infiltration via soil sediments. Groundwater contains little organic materials and has stable temperature and quality throughout the year (NGU, 2015b). However, the increasing demand of groundwater resources to fulfill the demand of growing population has led to the shrinking of water resources as the resources have not been sustainably used (Alley et al., 2002; Singh, 2014). This has led to groundwater contamination and depletion not only in the developing countries but also in the developed countries (Sophocleous, 2010).

The contamination of groundwater can occur from both natural sources and human activities. Natural sources include organic and inorganic compounds or elements present in the rocks and soils such as decaying organic matter, iron, manganese, arsenic, chlorides, fluorides, sulfates or radionuclides (Belk, 1994). Groundwater is mostly affected by waste disposal followed by agricultural activities, waste landfills, housing, mining, spills and road salt as the potential source of pollution (NGU, 2015b; Zaporozec, 1981). The contamination of groundwater also depends on the factors such as geographic location, wide range of environmental and physical variables, including soil type, depth to groundwater and aquifer size (Evans & Myers, 1990). The natural processes like oxidation, biological degradation and adsorption of contaminants to soil particles which occurs mostly in soil layers of unsaturated zone reduce the contaminants concentration thereby stopping it to reach the groundwater reservoir (Belk, 1994). The greater distance between the source of contamination and groundwater source might reduce the effects of contamination, since the infiltrated water requires relatively long time to pass through the soil layers towards the groundwater table.

Generally, groundwater moves slowly, with an exception through fractures in rocks where the movement is rapid. The movement of groundwater occurs along the flow paths from area of recharge to area of discharge (Alley et al., 1999). Therefore understanding the groundwater flow pattern of an aquifer is crucial step in monitoring the groundwater quality. The transport of contaminants within an aquifer occurs in the same manner as the groundwater flow pathway and depends on the physical, chemical and biological properties of the contaminants (Belk, 1994). The contaminants that are slightly soluble in water or strongly bind to the aquifer media move at a slower rate than groundwater flow (McCarthy & Zachara, 1989). The groundwater flow is also widely affected by factors such as recharge and interaction with the surface water.

Groundwater recharge is an important aspect of hydrological cycle. Recharge occurs as a result of precipitation that percolates to the groundwater system (McDonald & Harbaugh, 1988). Recharge involves the downward movement and influx of groundwater to an aquifer. Recharge occurs in places such as hills, erosional exposures of confined aquifers, alluvial fans along mountain fronts and ephemeral stream bottoms in dry regions. Besides geological settings of an aquifer, the climatic conditions such as precipitation as being the source of recharge to the aquifer plays a significant role to the groundwater flow (Sophocleous, 2002). The amount of rainfall and evaporation determines the water availability for infiltration. The area with higher evaporation than precipitation will have null infiltration and therefore the groundwater level in those areas will be deep below the surface of the ground (NGU, 2015b). The areal recharge might range from a tiny fraction to nearly half of the annual precipitation (Alley et al., 1999). Since the areal recharge occurs over wide areas, a small fraction of recharge might result in significant volumes of influx to groundwater reservoir.

The infiltration and the groundwater flow is largely dependent on the permeability of the soil sediments, as highly permeable soil sediments represent good infiltration and better groundwater flow (NGU, 2015b). The ability of the soil sediments to transmit water through it is determined by physical properties of the sediments such as size, shape, interconnectedness and void spaces between the sediment particles (Alley et al., 1999). The soil sediments may vary largely in mineral and chemical composition. The minerals present in the soil sediments might be exposed to the infiltrating water through different chemical processes such as mineral decomposition, chemical degradation, adsorption and ion exchange, thereby affecting the quality of groundwater (NGU, 2015b). The groundwater extracted from the permeable soil sediments have comparatively lower soluble elements than the groundwater extracted from the pumping wells inside the mountains. The water trapped between the bedrocks have higher residence time due to its impermeable nature thereby allowing enough time for the minerals present in bedrocks to easily dissolve in water under favorable conditions.

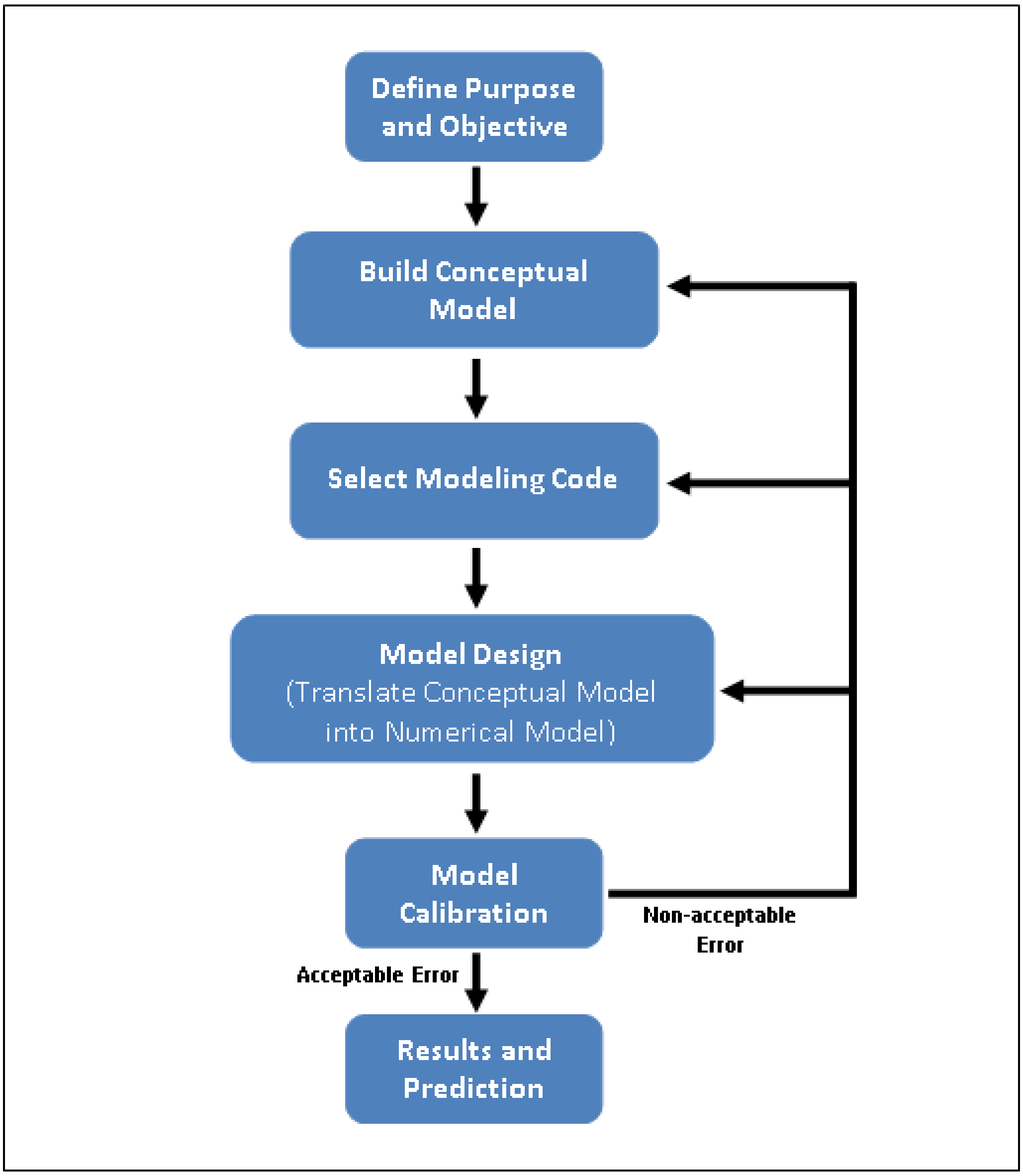
The interaction between the surface water and groundwater is very important in the groundwater flow process. The surface water resources are fundamental parts of the groundwater system since the surface water also act as a source of recharge to the groundwater even though they are separated by an unsaturated zone (Winter, 1999). In addition, groundwater also acts as an important source of surface water. It has been estimated that around 40 - 50% of water in small and medium-sized streams come from groundwater (Alley et al., 1999). Most of the rivers act as both recharge and discharge source. The direction of flow between the groundwater system and the surface water resources may vary from season to season depending on the change in altitude of the groundwater table with regard to the surface water altitude. The flow system between the aquifer and river depends on both the hydrogeological characteristics of the soil/rock material and landscape position (Winter, 1999). The rivers that gain water from the aquifer is in direct contact by a continuous saturated zone, whereas the rivers that loose water to the aquifer may be either connected by a continuous saturated zone or disconnected from the groundwater system by an unsaturated zone (Alley et al., 1999).

Aquifer or pumping wells that draw water from nearby streams, lakes or rivers have higher potential for contamination if the surface water resources are contaminated (Belk, 1994). Thus the importance of interaction between the surface water and groundwater has been the point of concern to find the sources of pollutant from the capture zones such as deposition of pesticides, eutrophication and acid rain (Sophocleous, 2002) and for effective management of drinking water system from groundwater resources (Winter, 1999).

Other factors that affect the flow to or from the aquifer is aquifer anisotropy, the properties and thickness of the river clogging layer, the changing stream water levels and the lateral boundary condition of the flow domain (Osman & Bruen, 2002). In the flood period, the river looses water to the banks and the infiltration occurs to the aquifer, which also reduces the risk of flood level. The amount of infiltration to the aquifer depends on volume of bank storage, height and shape of flood hydrograph and also the transmissivity and storage capacity of an aquifer. These stored water compensates to the flow during dry period (Brunke & Gonser, 1997).

2.2 Groundwater modeling approach

Groundwater flow model is one of the methods to monitor groundwater quality. A groundwater flow model is a representation of real aquifer situation, which simplifies the complexity of the geohydrological parameters and conditions into numerical and graphical form.



Source: (Anderson et al., 2015)

Figure 2-1: Groundwater flow modeling process

The groundwater flow modeling process (*Figure 2-1*) starts with the identification of purpose and objective of the model. The objective of the model helps to organize the necessary features of the aquifer system and its degree of accuracy that needs to be represented in the model (Bear & Verruijt, 2012). The purpose of developing groundwater models vary from study to study and might include objectives such as aquifer parameters estimation; understanding of the past and present of the groundwater systems; and predicting the future scenario based on assumptions and simulations (Anderson et al., 2015, p. 9; Reilly & Harbaugh, 2004, p. 3). The objective of the study determines how simple or complex the model development process can become (Bear & Verruijt, 2012). The cost, time, man power and technical requirement for the model development increases with the complexity of the model. Therefore it is necessary to simplify the objective and purpose of the model that best suits the available resources.

Followed by this step, a conceptual model is built that describes the phenomenon of flow and solute transport in an aquifer. The conceptual model is developed based on the information from field data related to geomorphology, geology, geophysics, climate, vegetation, soils, hydrology, hydrochemistry/ geochemistry and anthropogenic aspects (Anderson et al., 2015, p. 30; Kolm, 1996).

Later, these phenomenon are transformed into modeling codes to set in a computer program/software and hence called a numerical model (Holzbecher & Sorek, 2005). According to Anderson and Woessner (1992)

> *"a mathematical model simulates groundwater flow indirectly by means of a governing equation thought to represent the physical process that occur in the system, together with equations that describes heads or flows along the boundaries of the model."*

Furthermore, a mathematical model depends upon the solution from the basic equation of groundwater flow, heat flow and mass transport. The Darcy's law is the most simple mathematical model used for groundwater modeling among others (Fetter, 2000). The Darcy's law as expressed in terms of hydraulic head is denoted by the equation:

$$Q = -KA \frac{dh}{dl}$$

where,

Q is the discharge velocity in units of volume per unit time, *K* is the hydraulic conductivity, *A* is the flow cross-sectional area of the aquifer and d*h/*d*l* is the hydraulic gradient of the groundwater. The *dh* denotes head difference whereas d*l* denotes distance between points in the aquifer.

The general equation for flow in three dimensions (Fetter, 2000) is given by the partial differential equation:

$$\partial\left(\frac{\partial h}{\partial x}\right) K_x + \partial\left(\frac{\partial h}{\partial y}\right) K_y + \partial\left(\frac{\partial h}{\partial z}\right) K_z = \frac{\partial h}{\partial t} S + R$$

Numerical models are the transformation of the differential equation into discrete form. The discrete forms e.g. hydraulic head in flow model, concentration or temperature in transport model are determined as nodes and grids in the model domain (Holzbecher & Sorek, 2005). There are five types of numerical methods used in the groundwater modeling. They are finite difference, finite elements, finite volume, the boundary integral equations and analytical elements. The boundary integral equations and analytical elements are new technique and are not widely used (Anderson & Woessner, 1992; Holzbecher & Sorek, 2005).

The finite difference method is derived from the following differential equations:

$$\frac{\partial f}{\partial x} \approx \frac{f_{i+1} - f_{i-1}}{2\Delta x}$$

$$\frac{\partial^2 f}{\partial x^2} \approx \frac{f_{i+1} - 2f_i + f_{i-1}}{\Delta x^2}$$

where,

f-values denote function values at the grid nodes, that is f_i is the approximate value of the function at the node, and f_{i+1} at the following node and f_{i-1} at the previous node. The finite difference grids are usually rectangular and may be irregular which means that each column, row or layer may have individual grid spacing (Holzbecher & Sorek, 2005).

The finite difference numerical solution for steady state flow (Fetter, 2000; Wang & Anderson, 1982) is:

$$h_{i,j} = (1/4)\left(h_{i-1,j} + h_{i+1,j} + h_{i,j-1} + h_{i,j+1}\right)$$

Similarly, the method of finite volume is derived from mass or volume balance for all blocks of the model region and is obtained by the equation:

$$\frac{\partial V}{\partial t} = Q_{i-} + Q_{i+} + Q_{j-} + Q_{j+} + Q$$

where,

V denotes the volume or mass in the block, Q_{i-}, Q_{i+}, Q_{j-}, and Q_{j+} are the fluxes across the block edges, and Q other source or sinks for volume or mass.

The grids in finite element models vary in shapes, but mostly observed as the simple triangular form of the single elements (Holzbecher & Sorek, 2005).

After the completion of numerical modeling, the model needs to be calibrated so that any errors in the designed model are reduced to minimum thereby representing the real scenario of the groundwater system for further analysis and simulations. Model calibration is based on the calculation of the calibration target (which in most cases is hydraulic heads), by altering the model parameters such as transmissivity, recharge, boundary conditions etc. and comparing the calculated value of the target with the observed values from the field. The comparison of the calculated and observed calibration targets is done using summary statistics like mean error (ME), mean absolute error (MAE) or root mean squared error (RMSE) (Anderson et al., 2015, p. 391). The numerical formula to calculate these statistical measures are presented below:

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i^2}$$

where,

h_m = observed heads

h_s = calculated heads

n = number of targets

These summary statistics are used as criteria for goodness of fit, which determine how close the calculated parameters lie to that of the observed parameters. Out of these three statistical measures, RMSE is less robust to the effects of outlier residuals and therefore is most widely used for comparison between calculated and observed targets (Anderson et al., 2015, p. 392). Most of the studies use RMSE value to be 10% or less than that of observed head range as a criterion to determine best fit. However, there is no particular guideline available that suggest the acceptable magnitude of the summary statistics other than the fact that the errors should be as minimum as possible. Therefore, it has been suggested that subjective assessment of the calibration result by the modeler is required and the result of calibration should be based on the modeling objectives (Anderson et al., 2015, p. 392). Reilly and Harbaugh (2004) suggest that the result of the calibration should not always be based on the quantitative measures of goodness of fit; rather the focus of calibration should be on the appropriateness of the conceptual model that represents the study area, thereby allowing the modeler to adjust the conceptual model during the calibration process. This further leads to development of a model that has better fit, weighted residuals and more realistic optimal parameter values according to a well-argued conceptual model with minor adjustments (Hill, 1998; Reilly & Harbaugh, 2004).

A groundwater flow model can be calibrated either manually using trial-and-error method or automatically using parameter estimation programs like PEST or UCODE that is available in PMWIN. The manual calibration process might be time-consuming as it requires numerous model runs by manually changing the parameters values to get the desired calibration result. However, automatic parameter estimation program runs the model automatically by changing the values of the parameters within the given range provided by the modeler and presents the nearest possible values of the calibration targets that meets the observed values. Even though automatic calibration method is less time-consuming; it is recommended to calibrate the model initially via manual method in order to understand the behavior of the groundwater model with the change in parameters (Anderson et al., 2015).

2.3 Components of groundwater model

The accuracy of a numerical model depends on how closely the conceptual model is to the real aquifer system (Anderson et al., 2015). Therefore, it is crucial to spend enough time to build a good conceptual model. The conceptual model is expressed in words and consists of set of assumptions extracted from information of the aquifer domain (Bear & Verruijt, 2012). The assumptions in the conceptual model are related to the geometry of aquifer boundaries, geological composition of the aquifer, presence of assumed sharp fluid-fluid boundaries such as surface water, sources of water or relevant pollutants, effects of climate etc.

One of the vital component of a groundwater model is the boundary conditions. The definition of the boundary conditions of the model area is the most critical step of the modeling process (Franke et al., 1987). The boundary conditions in the model are determined from the hydrological conditions along the boundaries identified in the conceptual model (Anderson et al., 2015). The boundary conditions highly influence the flow directions of the model and include groundwater divides, bodies of surface water and relatively impermeable rock such as unfractured granite, shale and clay.

The boundary condition are mathematically divided into three types, namely specified head boundary, specified flow boundary and head-dependent boundary. In the specified head boundary also called Type 1 boundary or Dirichlet condition the heads along the boundary may vary in space or remain constant as in case of constant head boundary in which the head along the boundary is set to same or a known value (Anderson et al., 2015). The specified head boundaries are best used to represent large bodies of water (major rivers, lakes, reservoirs and ocean) that are not affected by stresses in the system such as pumping and changes in recharge rate. Both the specified head boundary and constant head boundary act as an inexhaustible source of water in the model and continuously provide required amount of water irrespective of the volume pumped even if the amount is not physically reasonable in the real system (Franke et al., 1987).

A specified flow boundary called Type 2 or Neumann conditions is implemented by setting the flow at the boundary as a function of position and time (Anderson et al., 2015; Franke et al., 1987). The derivative of head at the boundary is specified and the flow is calculated using Darcy's law. It is also called no flow boundary if flow across the boundary is specified as zero. Similarly, the head dependent boundary also called Type 3 or Cauchy conditions is a mixed boundary where flow across the boundary is calculated from Darcy's law using a gradient calculated as the difference between a specified head outside the boundary and the head computed by the model at the node located on or near the boundary.

In addition to boundary condition, sources of recharge to the aquifer is important to develop a model. The recharge can be in the form of precipitation or from surface water bodies. Among these two, areal recharge is of utmost importance to the aquifer, as it determines how much water can infiltrate into the aquifer. In addition, it also determines whether the surface water resources gain water from or loose water to the aquifer (Alley et al., 1999). Since recharge is difficult to calculate directly (Rose, 2009), precipitation data of the study area at the time of hydrologic analysis can be used in the modeling process to estimate areal recharge. Similarly, river profile data comprising of water level data of the river can be used to represent recharge or discharge via surface water. Due to the complexity of having exact values of recharge or discharge of the aquifer at a given time period, these parameters need to be calibrated.

The flow pattern of the groundwater along the aquifer is determined by the transmissivity of the aquifer media. The transmissivity can be estimated from the hydraulic conductivity and is correlated to soil properties like texture, pore size and grain size distribution. The transmissivity values to be used in the modeling process thus can be obtained from the grain size distribution of the soil sediments during drilling of the well. However, in case of lack of transmissivity values from the field data, these also need to be calibrated.

2.4 Applications of groundwater models

A groundwater flow model can be designed as physical scale models, analog models or mathematical models (Fetter, 2000). The calibrated groundwater model can be used for various hydrologic investigation purposes including but not limited to vulnerability assessments, remediation designs, and water quality and quantity estimation (Jyrkama et al., 2002), performing complex analyses and also making informed predictions (Anderson & Woessner, 1992; Paz, 2009).

The computer based stimulation model for groundwater flow system numerically evaluates the mathematical equation governing the flow of fluids through porous media (Reilly, 2001). Depending on the type of study and requirements for analyses, groundwater flow models can be either a simple one dimensional flow model for a local area (Gerla & Matheney, 1996) or a complex three dimensional flow model for regional to national level (Brodie, 1998; Kennett-Smith et al., 1996; Vermulst & De Lange, 1999).

The groundwater flow model can be used for analyzing the groundwater interaction, effect of pumping on the well field, and groundwater flow pattern (Singh, 2014). The mathematical model presented by Babajimopoulos and Kavalieratou (2004) helps to understand the water movement in a confined or unconfined aquifer. In another study, Aquifer Simulation Model for Windows (ASMWIN) has been used to develop mathematical models in order to verify the response of the aquifer to changes in well parameters and scenarios such as well extraction and contaminant injection to the aquifer (Paz, 2009). Singh (2014) has reviewed various groundwater models developed in the past and discussed the use of remote sensing and geographical information system (GIS) in groundwater modeling. Furthermore, GIS tools also helps in data preparation, processing and presentation of modeling results (Singha et al., 2016).

3 The Hagadrag Aquifer

3.1 Geographical location

The Hagadrag aquifer lies in Bø and Seljord municipalities of the Telemark County in the southeastern part of Norway. The aquifer is situated at 59° 25’ 54” N latitude and 08° 52’ 17” E longitude. The aquifer has an area of 1576 da (decare) (Trollsås et al., 2005). Agricultural land, camping place, forest and residential areas surround the aquifer. Road Rv.36 passes through the aquifer.

The aquifer functions as the major source of drinking water for around 5,900 residents of Bø municipality. In addition, the Bø river (*Bøelva* in Norwegian) is considered as the emergency source for drinking water in case of crisis (Vannregion Vest-Viken, 2014).

3.2 Surface water resources

The Hagadrag aquifer is located between three water resources in the region namely Hønsåa, Lake Seljord and Bø river (*Figure 3-1*). The Bø river runs across the aquifer from Northwest to Southeast. Kupatjønn and Herretjønn are two large kettle holes situated in northeast area of the aquifer. There is also a creek flowing from Kupatjønn. Water infiltration either from precipitation, snowmelt and Bø river, Hønsåa, Herretjønn, Kupatjønn and their watershed (*Figure 4-8*) are the major sources of recharge into the aquifer.

3.3 Bedrock geology

Granitic gneiss is the dominant bedrock in the study area. According to Sigmond et al. (1997), bedrock formation in the area of Hagadrag aquifer consists of well-preserved Precambrian metasedimentary and metavolcanic rocks known as the Telemark Super-group or the Telemark supracrustals as quartzite, amphibolite and metarhyolite are also found in the surroundings of Hagadrag (NGU, 2014).

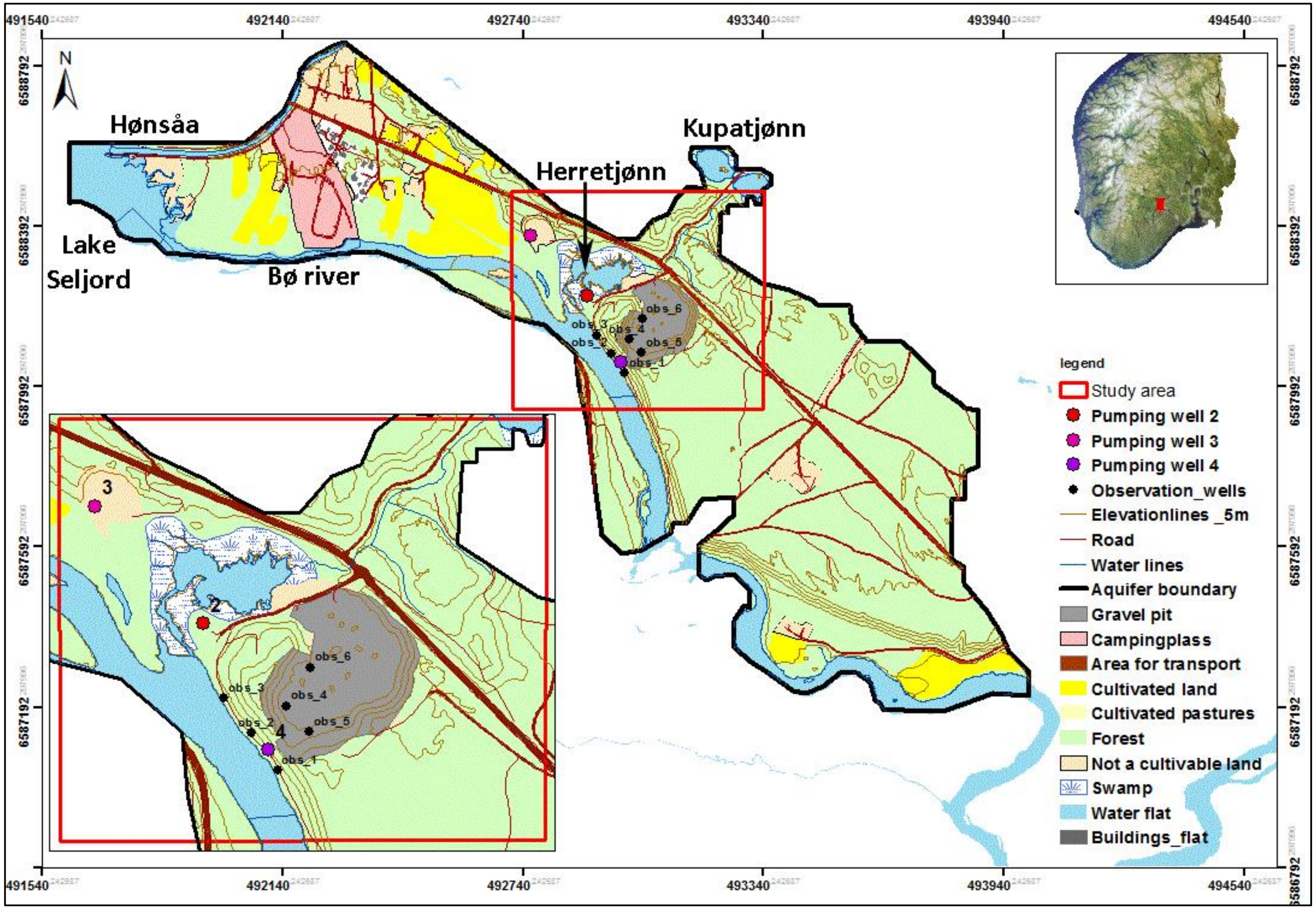
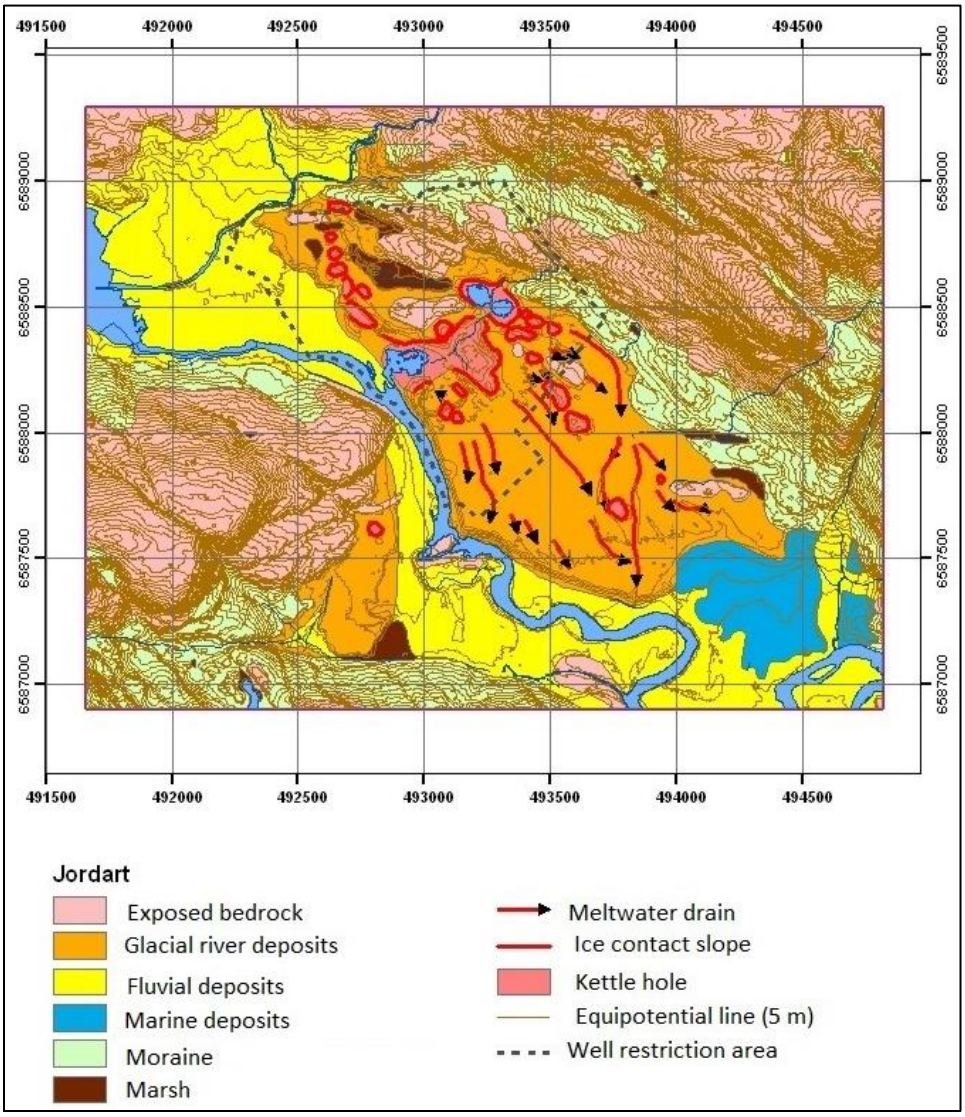


Figure 3-1: Map showing geographical location of the Hagadrag aquifer and wells

3.4 Quaternary geology

The major areas of the Central Telemark are dominant by permeable quaternary glaciofluvial deposits from the last ice-age, which consist of aquifers. The precipitation and infiltration from streams coming from watersheds of different sizes nourishes the aquifers which are developed from preamble deposits (Klempe, 2015). The regions around which the wells are situated consist of glaciofluvial and fluvial delta deposits as shown in picture below (*Figure 3-2*).



Map source: (Jansen, 1980; Klempe, 2010)

Figure 3-2: Quaternary map of the Hagadrag aquifer

It has the marine deposits that lie around 134 meters above sea level (m a.s.l.) and according to Jansen (1983) the aquifer belongs to the fluvial plain formed approximately 9500 Before Present (BP) years. This resulted in the deposition of stones, blocks of gravels and sand in the topmost layer having a thickness of 20 - 40 meters (m) whereas bottom layer consists of fine sand, silt and clay.

The glaciofluvial deposits are extended little further towards the northern side and have the kettle holes. At the northwestern side, the surface has contact with the Bø river. The groundwater level is similar with the river level at this area that is also known as saturated zone. This saturated zone is about 115 m a.s.l. at the side of Herretjønn and then sinks about 106 m a.s.l. down against Vegheim that lies in southeast of deposits. The unsaturated zone has sand and gravel alongside river that has the thickness of 15-25 m.

3.5 Climate

The study area has cold temperate climate i.e. cold winter and long mild summer. According to the Norwegian Metrological Institute[3], the most recent 30-year (1961-1990) annual mean precipitation in Bø was around 810 mm distributed evenly throughout the year. The annual mean temperature for the 30-year period was around 5.3^{o}C; December and January months being recorded as the most coldest months with average temperature below 0^{o}C. The winter is freezing cold that is why the precipitation is in the form of snow. At this time of year there is very less infiltration of water in the groundwater table in comparison to the summer season.

3.6 Pumping wells

The water requirement of the residents in Bø municipality is fulfilled by pumping water through two out of three pumping wells (*Figure 3-1*) at regular intervals. The municipality has in total four pumping wells; however, one of the pumping wells (pumping well 1) had been decommissioned in 2011 due to clogging and high concentration of iron and manganese. The oldest of these pumping wells is pumping well 2 (drilled in 1978) and the newest one is pumping well 4 that have been in operation since 2012 to replace the

[3] Source: https://www.yr.no/sted/Norge/Telemark/B%C3%B8/B%C3%B8/klima.html#år

pumping well 1. All the pumping wells are located in core deposits that are dominated by self-draining materials like sand or gravel (Ramberg, 2009). The three pumping wells have the capacity to pump 150 m^3/hr each. As mentioned earlier these wells are pumped at regular intervals, and all together pumping of 300 m^3/hr of water is needed to meet daily water requirement of residents in Bø (Kraft, 2011).

The pumping well 2 is situated in esker near the pond named Herretjønn which is a marsh lake that also opens into Bø river. The soil deposits in which the pumping well 2 is located consists of sand and gravel. The well is 22 m deep and has two filters; one between 12 - 16 m and another between 18 - 21 m. This well is near to the gravel pit and has a big threat from it. The pumping well 3 is situated in esker on the farming land and has residential areas and camping place nearby. The well is 30 m deep with filter at 25 - 30 m. The pumping well 4 which is 23 m deep had been constructed on the close proximity of the Bø river and is the mostly used well for supplying water to the households in Bø municipality. The filter tube in this pumping well hangs from 7 to 22 m down the well with 0.1 mm spacing between each filter.

In order to test the pumping well 4 and its surroundings before its operation, six observation wells (*Figure 3-1*) were constructed around the well. Out of the six, three observation wells namely well 1, 2 and 3 are located near the Bø river, whereas the other three observation wells 4, 5 and 6 are located inside the gravel pit. The observation well 6 lies close to the main road between Bø and Seljord. The observation wells 1, 2 and 3 are separated from observation wells 4, 5 and 6 by a hill formed by a glacier during the last ice-age period.

The grain size distribution across 1 m depth interval inside the aquifer from soil samples obtained during drilling of these observation wells indicate that the area is highly dominated by well-sorted sand and well-sorted gravel (*Figure 3-3*).

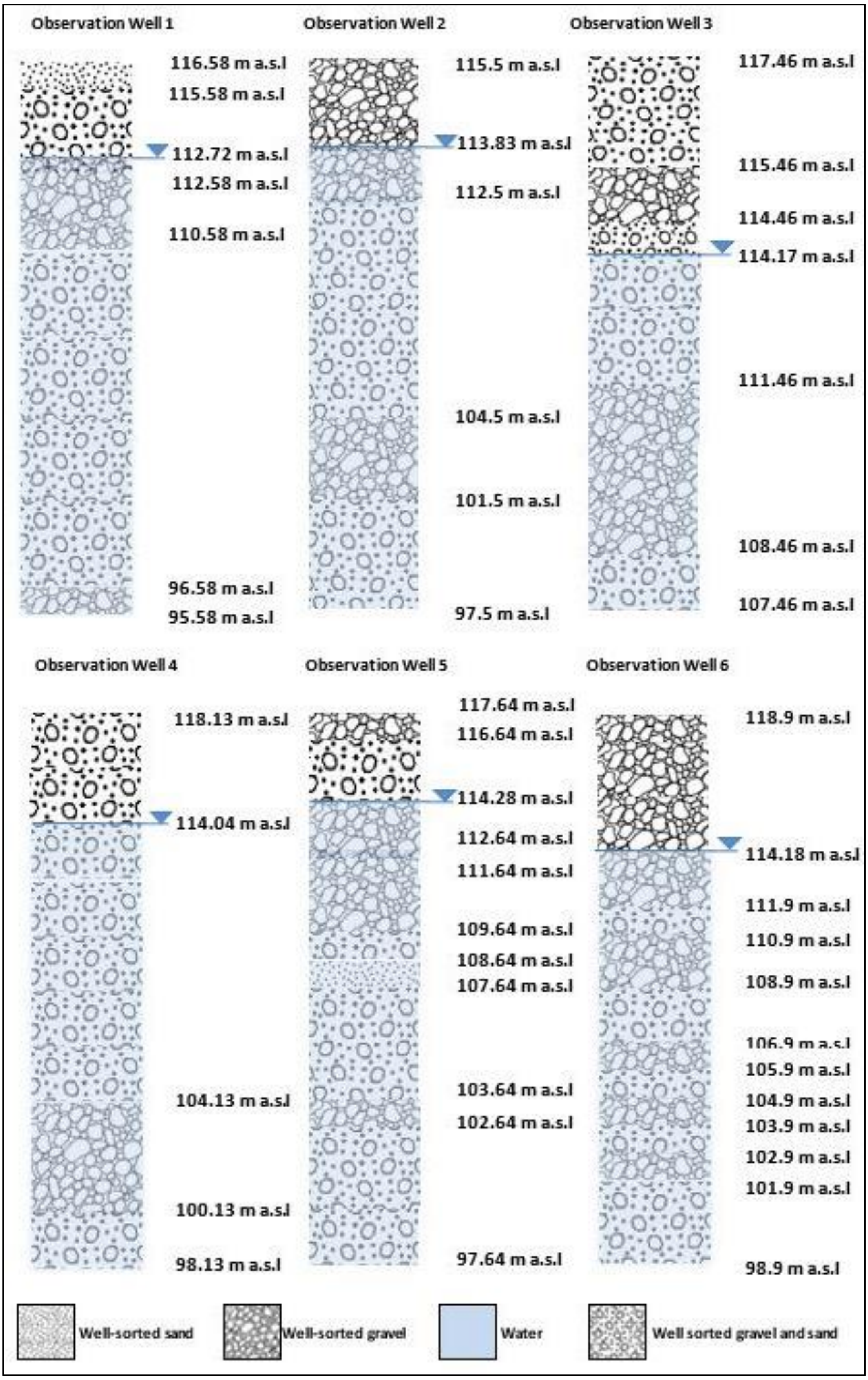


Figure 3-3: Grain size distribution of soil samples in observation wells

Each of the test wells has three hosepipes (with a filter at the end of each hosepipes), each having a diameter of 32 mm, with its opening at three different depths of nearly 6 meters, 12 meters and 20 meters inside the well (*Figure 3-4*). A metal tube of 15 cm diameter protects the hosepipes. In order to ensure that the samples represent the constituents and properties of the overall well, water samples were collected from three different depths within the same well.

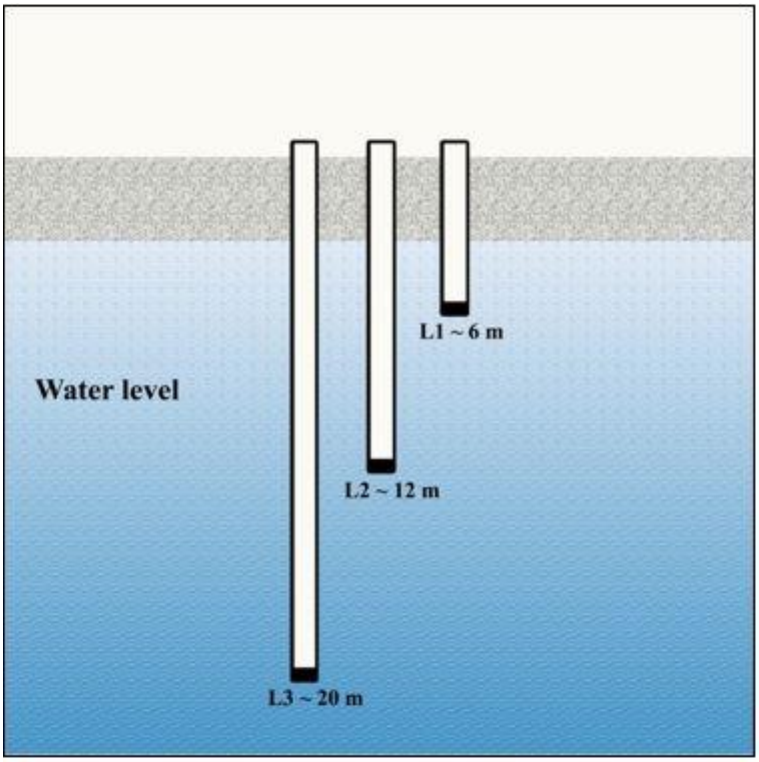


Figure 3-4: Sketch of a multilevel arrangement of observation well

The pumping well 2 and 3 lies very close to the road Rv.36 which is heavily treated with de-icing agent (salt) during winter. However, studies have shown that the quality of drinking water supplied in Bø has not been compromised by salting until today (Kalauz, 2014; Solli, 2016).

3.7 Water quality at the study area

The quality of water extracted from the aquifer for household purposes has been evaluated to be of good quality and within the recommendations provided by the Norwegian standard, with some low pH and high manganese concentration (Aarnes, 2015; Kalauz, 2014; Kraft, 2011). The manganese concentration is mostly higher in pumping well 2 and Herretjønn. The manganese concentration in Herretjønn is reported to be higher at the bottom than the surface ranging from 0.21 mg/l to 0.27 mg/l at the bottom and 0.02 mg/l to 0.05 mg/l at the surface (Ramberg, 2009). It has been argued that the high concentration of manganese in pumping well 2 can be result of infiltration from Herretjønn (Kraft, 2011) which has high amount of organic material and low dissolved oxygen (DO). As the DO reduces in the groundwater, the microorganisms present in the groundwater bodies continue to degrade the organic carbon as source of energy and carbon, thereby producing carbon dioxide (CO_2) which further decreases the pH of the water. During this process, the organic carbon is oxidized to CO_2 and oxides of manganese which is insoluble gets reduced to soluble Mn^{2+} states (Young, 1903).

The major quality concern for the aquifer is the chloride contamination because of the de-icing salt used in road Rv.36. The chloride concentration of the three pumping wells varies greatly. The analysis of pumping test conducted between April 2013 and March 2014 show that pumping well 4 is least affected by chloride contamination with concentration ranging from 2 mg/l to 4.5 mg/l (Kalauz, 2014). The pumping well 3 has chloride values ranging from 2.1 mg/l to 22.7 mg/l. Among the three pumping wells, pumping well 2 has relatively higher chloride values ranging from 5 mg/l to 40 mg/l.

The chloride concentration of the Bø river, Hønsåa and the creek flowing from Kupatjønn have lower values around 1.75 mg/l, 1.18 mg/l and 1.77 mg/l respectively (Kalauz, 2014). On the other hand, the chloride concentration of Herretjønn increases with the depth of the pond (Kalauz, 2014; Ramberg, 2009) and has higher values than the surrounding surface water resources ranging from 5.62 mg/l at the surface up to 51.46 mg/l at 7m depth posing threat to the groundwater.

The higher chloride and manganese values in both the pumping well 2 and Herretjønn gives an indication that Herretjønn can be one of the contamination source for the Hagadrag aquifer.

4 Methods

4.1 Objectives of the study

This study has been designed to develop groundwater flow model of the Hagadrag aquifer by using Processing Modflow[4] (PMWIN) and Arcmap[5] software as modal processors. The main objective of the groundwater flow model developed in this study will be to identify the capture zones of the pumping wells when pumped together as in a steady state situation. This will further help to determine the flow pattern of water inside the Hagadrag aquifer and thereby predict the vulnerability of the aquifer from contaminants from the nearby sources if any might occur in future.

4.2 Study data

The data used to develop models in this study were extracted from national map data and previous studies on the study site.

4.2.1 National map data

The data from the online Norwegian databases acted as the backbone of this study. The data collected from these databases include map data and hydrological data of the study area. These data were used to gather background information of the Hagadrag aquifer thereby contributing to the development of conceptual model and assumptions in the modeling process.

i. FKB[6] data (Felles kart database)

FKB data are the collection of data sets, which together constitute a public map data. Norwegian map authority and municipalities provide these data. The database has different types of data for example water lines, water polygons, roads, buildings etc. (Mæhlum, 2016). The data from this database was provided by supervisor Harald Klempe,

[4] www.pmwin.net

[5] http://www.esri.com/

[6] http://www.kartverket.no/data/kartdata/Vektorkart/FKB/

since it required special authorization to access the database server. The data in this database are stored as shape files which can be easily readable in ArcGIS.

ii. NEVINA[7] (Nedbørfelt- Vannføring –Indeks-Analyse)

NEVINA is one of the map work tool of The Norwegian Water Resources and Energy Directorate (NVE). It is a simple user friendly GIS tool which generates catchment boundaries in scale 1:50000 from a chosen point in a water course and automatically calculates a range of climate, field and hyrdrological parameters and low tide indexes for an arbitrary catchments in Norway (NVE, 2015). The data in this database are available both as shape files and as reports from which specific information can be extracted.

iii. seNorge[8]

It is also one of the map tool developed by NVE and The Norwegian Meteorological institute[9], which visualizes the updated data for air temperature, discharge, precipitation, ground water table and wind speed from various metrological stations in Norway. The data in this database are stored for several time periods, like daily, weekly or yearly and the required data can be extracted either as graph representation or as data excel file.

4.2.2 Field data

The field date used in this study include hydraulic head data from data loggers and hydraulic conductivities from grain size distribution of the aquifer layers around pumping well 4 and observation wells. These data were extracted from previous studies that involved drilling and pumping tests (Aarnes, 2015; Kalauz, 2014; Klempe, 2011; Trollsås et al., 2005). The head potential data constitute the observed hydraulic head values that were used for calibration of the model and hydraulic conductivity data were used to calculate transmissivity values to develop the model.

[7] http://nevina.nve.no/

[8] http://www.senorge.no/

[9] https://www.met.no/

4.3 Model processors

The model processors used in this study were Processing Modflow (PMWIN) and ArcMap to build groundwater models. Notepad and MS Excel were used as data handling tools to prepare the data as required by the model processors.

4.3.1 ArcMap

ArcMap is one of the map tools of ArcGIS software which is designed to capture, manage, analyze and display all forms of geographically referenced information (Esri, 2017). It is a user friendly tool that helps to handle the complexity of different spatial, physical and hydrological data and representing them through visualizing maps using layers and legends (Dawoud et al., 2005). It has been well established that combining GIS to process-based groundwater model plays an effective tool when using function such as data processing, storing, manipulating, visualizing and displaying hydrogeological information (Singha et al., 2016; Xu et al., 2011). In addition it can also be used directly as a linking tool for preparing input files for groundwater model MODFLOW (Orzol & McGrath, 1992) or an integrated step in analyzing and calibrating model based on visual representation of the model output (Brodie, 1998).

In this study, ArcMap 10.3 was used. ArcMap was used both as a pre and post processor for groundwater flow pattern in the PMWIN. The FKB data were visualized in the ArcMap that provided many information of the study area. The projected coordinate system used in ArcMap was WGS 1984 UTM Zone 32N.

As a pre-processor, the ArcMap helped to visualize the surroundings of the study areas like roads, gravel pits, river, well location etc. that was a part of conceptual model in this study. In addition, ArcMap was used to narrow down the whole study area to modeling area (*Figure 4-2*) and creating Thiessen polygons for transmissivity values (*Figure 4-5*). Creating Thiessen polygon is one of the proximity tools in ArcToolbox, which is used to divide the area covered by input point features into Thiessen. The Thiessen polygon method uses only one nearest point from the sampling location to interpolate the value to the unsampled location (Zhu, 2016). Each location within a polygon has a value equal to the polygon's sample point. The advantage of Thiessen polygon method over other interpolating methods in GIS is its less susceptibility to the outliers as it does not require large number of sample points.

As a post-processor tool, model and simulation results developed in PMWIN were extracted in ArcMap to visualize hydraulic heads, capture zones and flow patterns.

4.3.2 Processing Modflow (PMWIN)

PMWIN is a modular three-dimensional finite difference groundwater modeling software, which describes and predicts the behavior of groundwater flow system (Chiang 2005). It is an important tool for managing water resources in aquifers and predicting how the aquifer might respond to the changes in pumping and climate variations (El Yaouti, El Mandour et al. 2008). The PMWIN is based on MODFLOW modal code developed by the United States Geological Survey (USGS) (McDonald & Harbaugh, 1988). The first version of MODFLOW was released in 1988 called MODFLOW-88 whose application was to describe and predict the behavior of groundwater flow systems. Later on, other versions were also released i.e. MODFLOW-81 and MODFLOW-96 which were designed to simulate saturated three dimensional groundwater flow through porous media. The latest version MODFLOW-2000 incorporates the solution of multiple related equations into a single code. The code is divided into the entities called processes and each process deals with a specific equation (Chiang 2005). In this study PMWIN version 8 was used that runs on MODFLOW-2000.

PMWIN allows selection of layer property package based on the available aquifer parameters. These parameters include horizontal hydraulic conductivity (HK), vertical hydraulic conductivity (VK), specific storage (S_s), transmissivity (T), vertical anisotropy (VANI), Storage coefficient of storativity (S) and specific yield or drainable porosity (S_y). The layer property package can be either Block-Centered Flow (BCF) or Layer-Property Flow (LPF). The storage coefficient and specific yield are only required for transient flow simulation. The BCF supports 4 layers types namely, strictly confined layer (Type 0), strictly unconfined layer (Type 1), partially convertible layer between confined and unconfined (Type 2) and fully convertible layer between confined and unconfined (Type 3); whereas LPF supports only layer Type 0 and Type 3. The parameters requirement for different layer types of BCF and LPF are presented in *Table 4-1*.

Table 4-1: Aquifer parameters for Block-Centered Flow (BCF) and Layer-Property Flow (LPF)

Layer Type	Aquifer Parameters	
	BCF	LPF
Type 0	T and S	HK, S_s and VK or VANI
Type 1	HK and S_y	Not applicable (N/A)
Type 2	T, S and S_y	N/A
Type 3	HK, S_y and S	HK, S_s and VK or VANI

The PMWIN provides various flow packages (Chiang, 2005) to support field data and simplify the modeling process. These flow packages help to simulate general head boundary (GHB) effects of drains, evapotranspiration, wells, rivers and recharge. In this study, recharge, GHB and well flow packages were used for modeling. In addition, PMWIN also supports automatic calibration, water budget calculation and capture zone visualization.

The automatic calibration also known as parameter estimation can be done using built in interface of MODFLOW -2000 or by using PEST or UCODE that are external interfaces integrated in PMWIN. The capture zone of the aquifer can be visualized using the advective transport model so called PMPATH in PMWIN. PMPATH is a post-processing tool that visualizes streamlines and flow paths. It also traces backward and forward particle tracking in time (Holzbecher & Sorek, 2005). It calculates the travel time and capture zones of groundwater flow. In addition it displays the head contours, drawdown contours and velocity vectors of the model layer (Chiang, 2005).

4.4 Modeling approach

The *figure 4-1* presents the framework showing sequential order used for modeling in this study. The modeling approach included the identification of the problem and definition of objective for the study; development of a conceptual model based on field data and information about the study area; and numerical modeling of the aquifer followed by calibration and visualization of flow patterns. The units used in this study were meter (m) for length parameter and days (d) for time parameters.

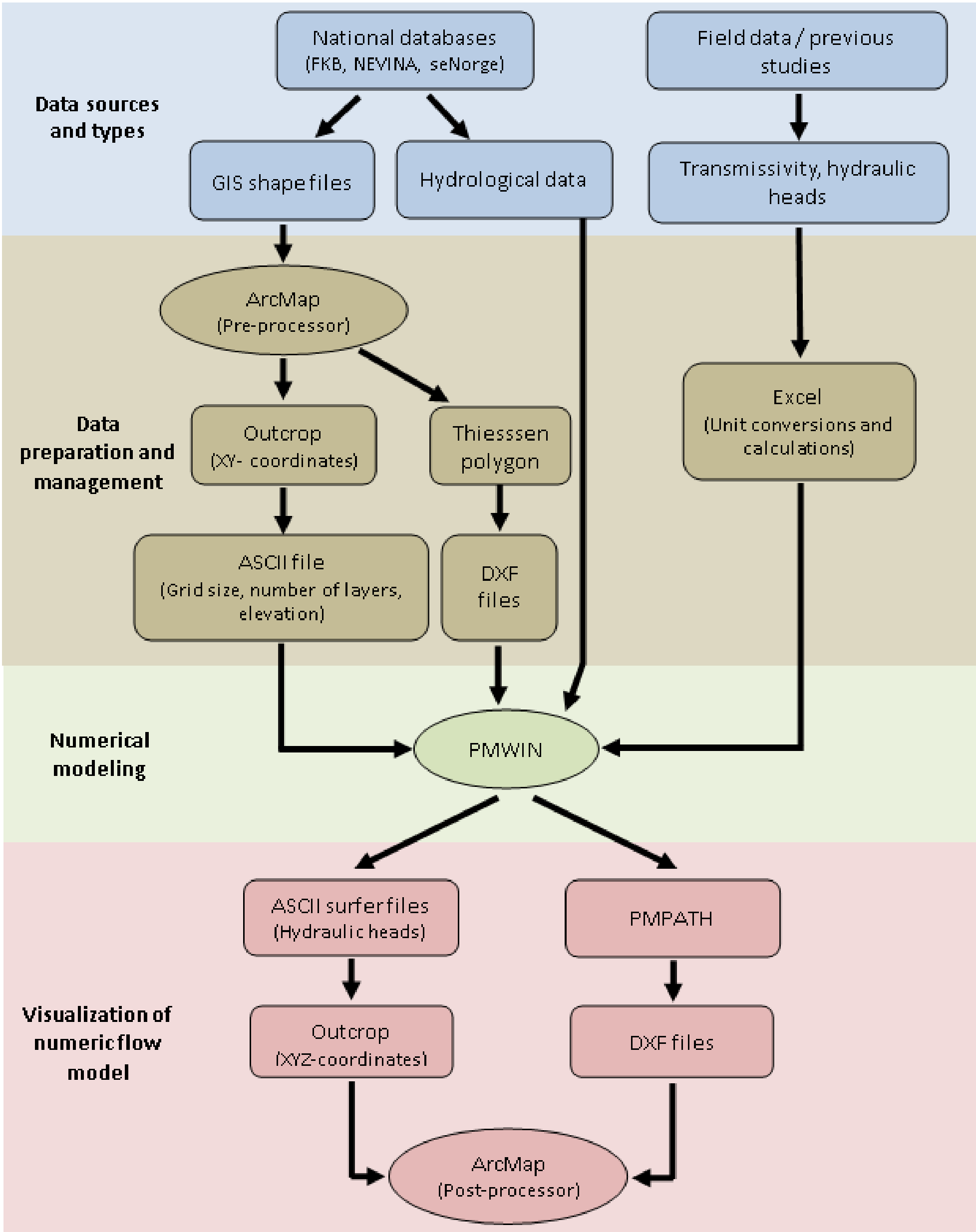


Figure 4-1: Framework for modeling approach

4.4.1 The conceptual model

The development of conceptual model was based on previous studies that provided background information about the study site. The Hagadrag aquifer up to now has been identified as both confined and unconfined aquifer. The nearby surface water resources Bø river, Kupatjønn, Herretjønn along with the precipitation in the form of rainfall and snowmelt are the recharge sources for the aquifer. The aquifer was assumed to be in steady-state flow.

In addition, the creeks from the Kupatjønn gave an idea that these can also be the recharge source from the watershed to the aquifer. The creeks are observed throughout the year but appears to be dry during very dry summer (*personal with Harald Klempe*). These creeks were therefore represented by four injection wells in the further modeling process.

The upstream part of the Bø river between end of Lake Seljord and Herretjønn appears to be somewhat flat suggesting a constant water level in that region; whereas the downstream part of the river below Herretjønn is more steep and might vary in water level across the river. The Hagadrag station that records water level of the Bø river is located at UTM-east: 492895 and UTM-north: 6588165, which is situated near the junction where Herretjønn meets the river. The water level of Bø river extracted from NVE database therefore relates to this area only, and therefore the downstream water level was extracted from the river profile data given by Bø municipality (*Appendix 3*). The hydraulic conductivity of the riverbed is difficult and uncommon to determine, therefore, it has been suggested to predict the hydraulic conductivities in the range between 10^{-7} and 10^{-3} m/s (Calver, 2001). The Bø riverbed is dominant with clay, sand and silt, thus hydraulic conductivity of the river bank was assumed to be 10^{-7} m/s, i.e. 0.00864 m/day (Fetter, 2000).

The discharge of water from the aquifer is mostly through water extraction during pumping. The pumping wells have maximum extraction capacity of 150 m^3/hr. However, the Bø municipality extracts water at the rate of 115 m^3/hr from pumping well 4. The pumping test during establishment of the pumping well 4 revealed that the pumping rate of 115 m^3/hr will maintain a stable water level at this well. The volume of water extracted by pumping varies between summer and winter season. Higher volume of water is extracted during summer season especially between June and early August because of the increased water requirement in Bø Sommarland. During this period, the pumping wells are run either together or most frequently than the winter season. This varying extraction of water from the aquifer gave an inference that the capture zones of the aquifer might vary during summer and winter period. This variation in the capture zones is further expected to be effected by amount of precipitation and volume of water available in the creeks.

4.4.2 The numerical model

The numerical modeling process started with the processing of hydrological, GIS and field data. PMWIN was used to develop groundwater flow model and ArcMap was used as pre-processor to extract data required in PMWIN and as post-processor to visualize the flow models. In addition, Notepad and MS Excel were used as helping tools in preparing the data.

The development of groundwater flow models in this study followed a stepwise progression. The modeling process started with development of a model of a small area, thereby extending the model to a larger area covering the Hagadrag aquifer. The development of small area model was my learning process to make groundwater flow models using PMWIN and ArcMap and also to see the effect of scale and boundaries. The description regarding development of the small area model are not presented in this thesis.

The small area model however helped to develop the idea of generating parameters in model and extending the model area. This model covered area for pumping wells 2 and 4 only. As the Bø municipality has three main pumping wells i.e. 2, 3, 4 it was necessary to extend the model area and simulate the water flow pattern in the aquifer when these three wells were pumped according to the program of the municipality.

4.4.2.1 Model grid and cell size

The study area was narrowed down to a model area by creating corner points in ArcMap (*Figure 4-2*) that represented geographical location in form of XY-coordinates. The XY-coordinates of the top left corner, lower left corner and upper right corner extracted from ArcMap were used in ASCII file (*Figure 4*-3) to be read by PMWIN. The ASCII file was created using Notepad according to the PM manual (Simcore Software, 2012, pp. 424-425) and saved as *.dat* file. The file consisted additional information related to grid size in rows and columns, width along rows and column, number of layers, and top and bottom elevation of each model cell. The grid and cell size in this model was 312 rows and 391 columns with a cell size of 2 m.

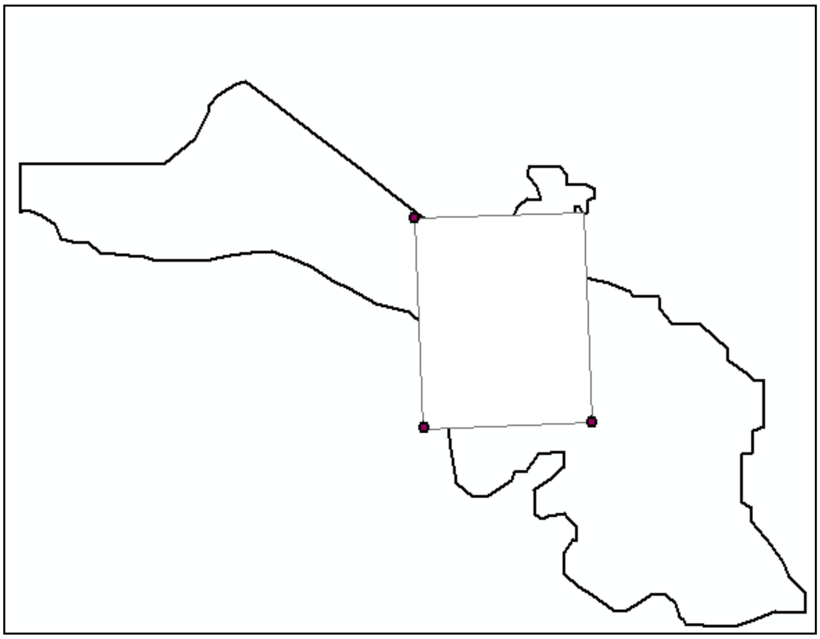


Figure 4-2: Extracting model area from study area using ArcMap

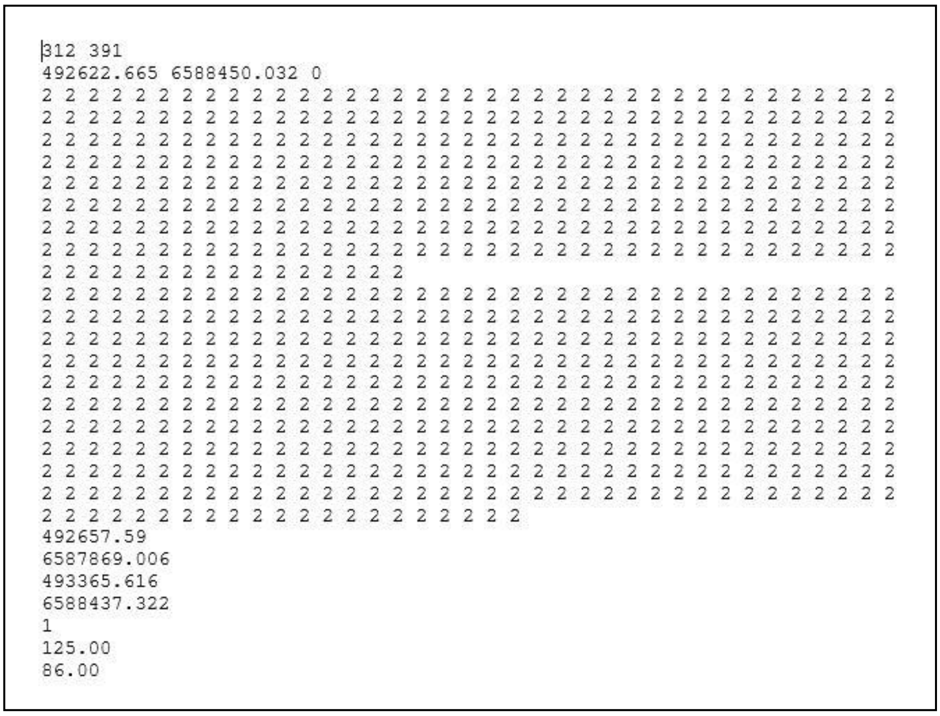


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Figure 4-3: ASCII file for model grid and cell size

4.4.2.2 Layer property

This model was designed as a single layer that represented a single hydrostratigraphic unit (Anderson & Woessner, 1992). The layer property was defined to be BCF. The term "Block centered" in BCF means that the node is located at the center of the cell.

Since Hagadrag aquifer has the layer property of both confined and unconfined aquifer, the Type 2 layer was used for the model development. Based on the assumption of steady-state flow, only transmissivity data were required for the model development. The transmissivity of each cell were constant throughout stimulation (Chiang, 2005).

4.4.2.3 Hydraulic Boundaries (IBOUND)

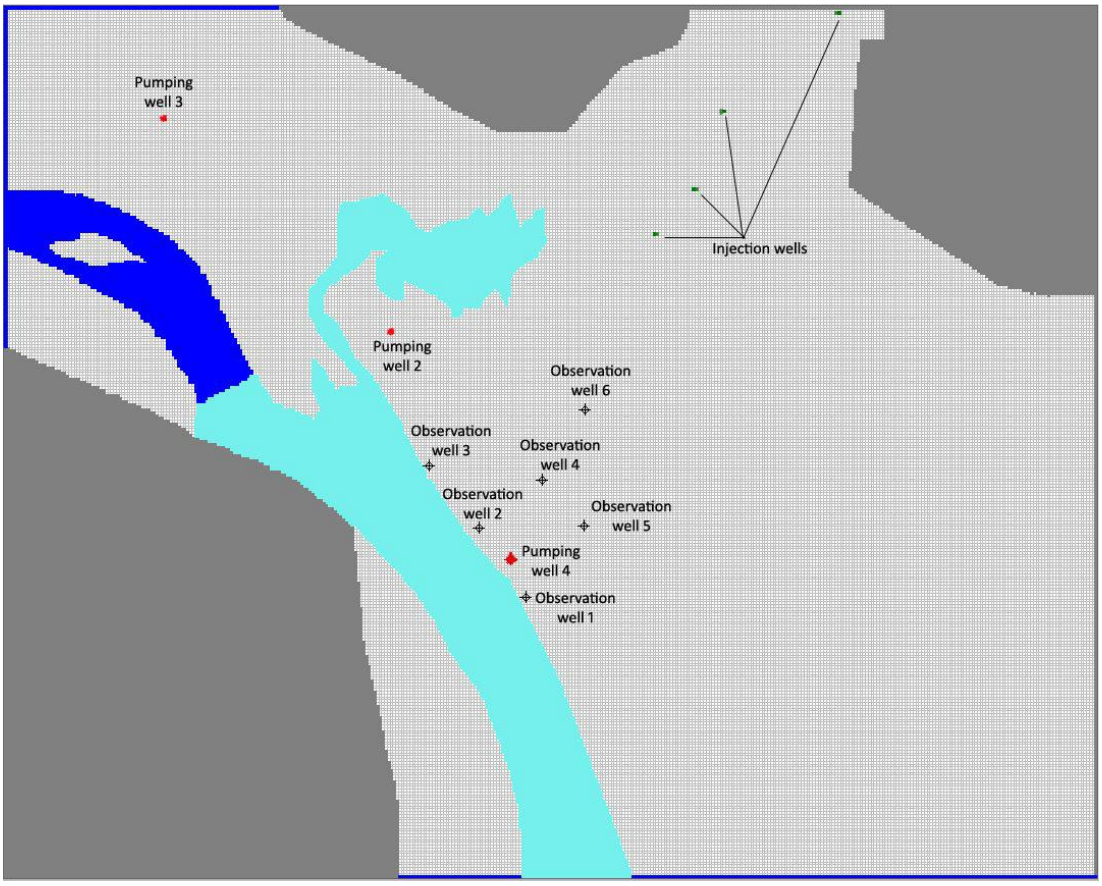

Figure 4-4: Hydrological boundaries and cell status in the model

The hydraulic boundaries in MODFLOW were made by giving the value to each cell in IBOUND cell status. MODFLOW requires specific codes (IBOUND arrays) to define each model cell (Chiang, 2005). The assigning values are -1, 0 and 1. The positive value "1" defines an active cell in which the hydraulic head is computed. The negative value "-1" defines a constant head or fixed head, where hydraulic head is kept constant at a given value throughout the flow stimulation. The value "0" defines the inactive cell, which means there is no flow entering to the model from that region. The flux boundaries with non-zero fluxes are simulated by assigning appropriate infiltration or pumping wells in the corresponding cells via the well package.

The *figure 4-4* shows the model area in the Hagadrag aquifer and the cell status in the model cells. The dark grey ones are the no flow boundary, dark blue are the specific head, and light grey are the active cells. These boundaries were given value as 0, -1 and 1 respectively in PMWIN. In real scenario, the dark grey cells area are bedrock. The red ones are the pumping wells and the dotted dark dark green are injection wells. The upstream part of the Bø river was considered to have constant head and thus given value for specific head in the model. The light blue color represents downstream of the river and Herretjønn both having Type 3 boundary. The detailed description of the river cells and well cells are explained in *Section 4.4.2.5* below.

4.4.2.4 Parameters

a. Initial and prescribed hydraulic head

MODFLOW requires initial hydraulic head at the beginning of flow simulations for constant head cells. These hydraulic heads in the model are used as specific head values of those cells and remain constant throughout the flow stimulation (Chiang, 2005). For this model, the constant head cells at the upper left corner and upstream of Bø river (represented by dark blue color in *figure 4-4*) were given initial hydraulic head value of 115 m (*personal with Harald Klempe*). The constant head cells on the lower end of the model area were given head value same as the water level of the Bø river in that end, which was determined from river profile report by Bø municipality.

b. Transmissivity

The model in this study represents heterogeneous model with varying transmissivity values. The transmissivity values for the area around observation wells were calculated from earlier work by Aarnes (2015), in which hydraulic conductivity was measured from grain size distribution across 1 m depth interval inside the aquifer from soil samples.

The transmissivity of each depth interval from soil samples was then calculated using the formula:

$$T_i = k_i \times m$$

$$T_t = \sum T_i$$

where,

T is the transmissivity, k is the hydraulic conductivity and m is the thickness of the layer, which is 1 m.

The total transmissivity of an area was then calculated by adding transmissivities of each layer in that area. In addition, the transmissivity values of the area besides observation wells were taken from the earlier report by Trollsås et al. (2005). The transmissivity of the area around pumping well 4 was calculated from data from grain size distribution during drilling of well 4 done in 2011 (Klempe, 2011).

The transmissivity Thiesssen polygon was made around every sample point in the ArcMap (*Figure 4-5*). Later the DXF file of Thiesssen polygon as a background map was imported in PMWIN and new polygons were drawn over those polygons (*Figure 4-6*) and each polygon were given its transmissivity values (*Appendix 2*).

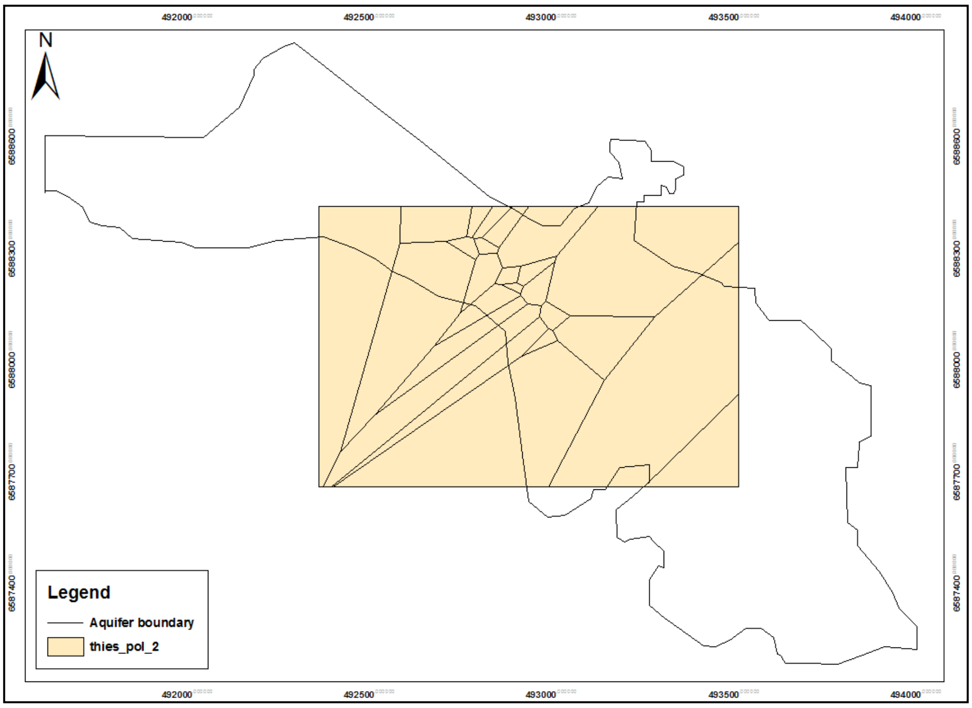

Figure 4-5: Map showing Thiessen polygon

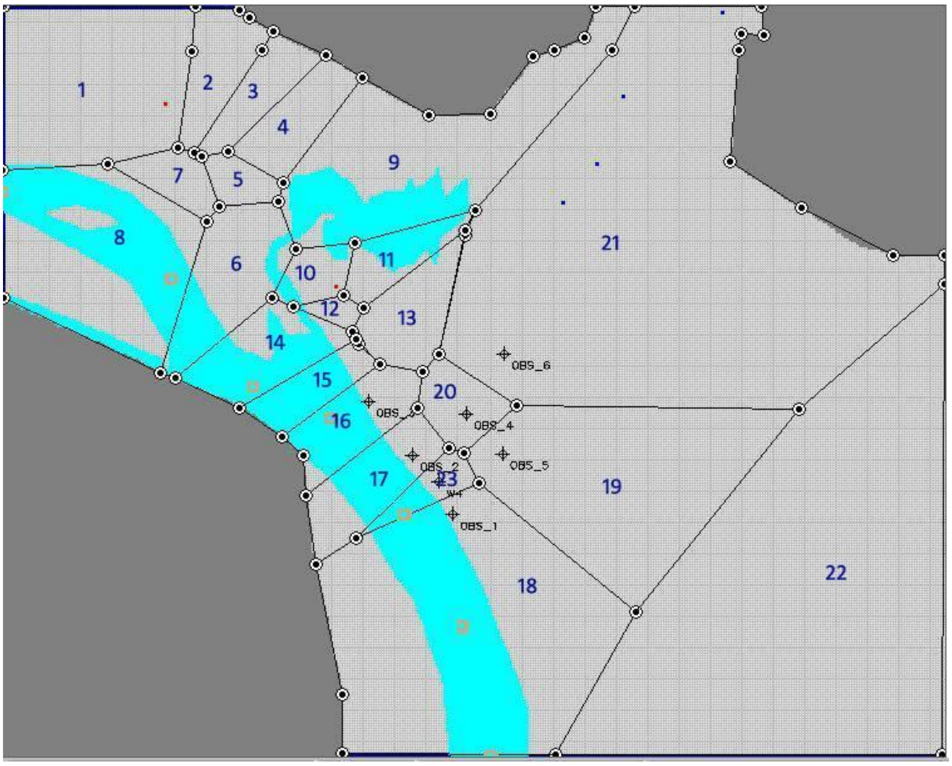

Figure 4-6: Thiessen polygon in PMWIN

4.4.2.5 PMWIN flow package

a. General Head Boundary (GHB)

The GHB package was used to represent the boundary condition of Herretjønn and Bø river downstream and was used to simulate the head-dependent flow boundaries. The data input for this package was done via Polygon method. The polygons were made along the Bø river and also in Herretjønn as shown in *figure 4-7*.

The input data required for GHB were hydraulic conductance of the riverbed and head in the river, which were extracted from the river profile data obtained from Bø municipality.

The hydraulic conductance of the riverbed for each polygon was calculated using the equation:

$$C_{riv} = \frac{K_{riv} \times l \times W_{riv}}{M_{riv}}$$

where,

Criv = hydraulic conductance (m/day)

K_{riv} = hydraulic conductivity of riverbed (m/day)

L = length of the river within a cell (m)

W_{riv} = Width of the river (m)

M_{riv} = Thickness of the riverbed sediments (m)

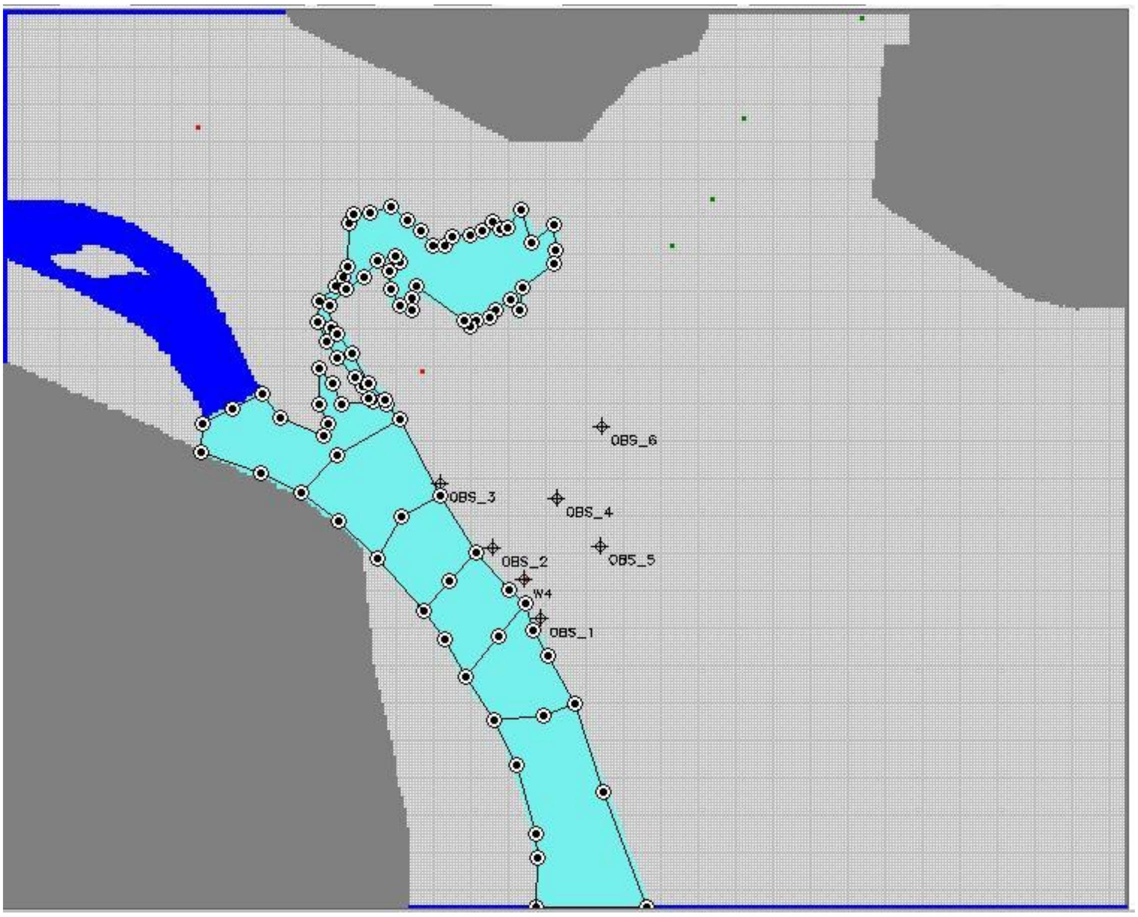

Figure 4-7: Polygons for GHB package

The hydraulic conductivity assumed in this model was 10^{-7} m/s, i.e. 0.00864 m/day as mentioned previously in *section 4.4.1*. The width of the river was measured in ArcMap. The thickness of riverbed sediments was assumed as 0.5 m (*personal Harald Klempe*). The input parameters for GHB package are presented in *Appendix 3*.

b. Wells

In MODFLOW the well package is designed to simulate feature such as wells which withdraw water from or infiltrate water into the aquifer at a specified rate during a given stress period. The rate to which water is withdrawn or added in is independent of the cell area and the head in the cell (McDonald & Harbaugh, 1988). MODFLOW assumes that a well penetrates the full thickness of the cell (Chiang, 2005).

In this study, three pumping wells i.e. well no 2, 3 and 4 and four injection wells were inserted (*Table 4-2*). The pumping wells withdraw water from the aquifer and the injection well adds water to the aquifer. The pumping wells have negative values and the injection well have positive value. The injection wells were hypothetical wells inserted to represent the creeks from Kupatjønn.

Table 4-2: Location of wells in the model area

		Rows	Columns
Pumping wells	2	117	139
	3	41	68
	4	198	182
Injection wells	1	82	233
	2	66	247
	3	38	258
	4	3	299

Since the pumping rate of the wells are 115 m^3/hr, the value inserted in this model was 2760 m^3/day. Similarly, the infiltration rate of the injection well was calculated from the watershed data extracted from NEVINA database (*Appendix 1*). The watershed, which feed Kupatjønn and Herretjønn, is shown in *figure 4-8* below. The watershed has an area of 1.1 km^2.The infiltration from the injection wells were assumed to be same. The total drainage of the watershed area was 11.22 l/s, that was divided equally to these injection wells giving a value of 121.176 m^3/day per injection well. The assumption behind dividing the flow rate by 8 was the half of the discharge from the creek drains to the aquifer and other half flows to the Herretjønn (*personal with Harald Klempe*).

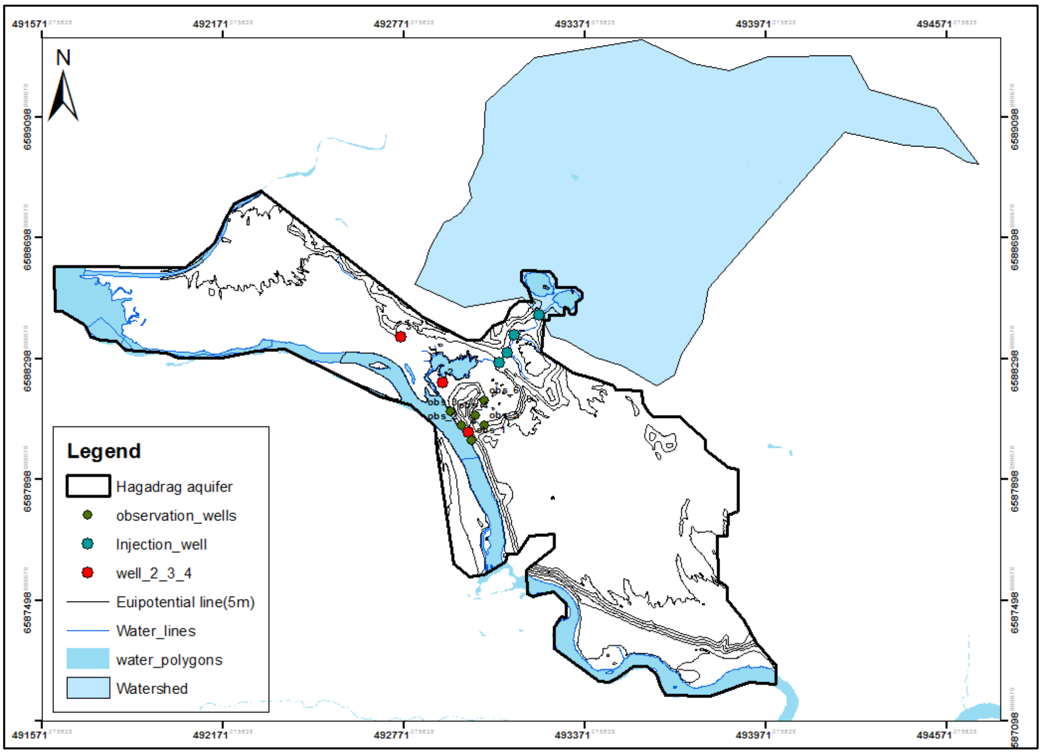

Figure 4-8 Watershed to Kupatjønn and Herretjønn

c. Recharge

An infiltration of 400 mm/yr was assumed in the area (*personal Harald Klempe*), which was converted to model units as 1095.89 m/day. The recharge was applied to the highest active cell since the aquifer receives much of the recharge from the precipitation. The reason behind choosing this option was to be less concerned about determining which the highest active cell was in a vertical column, since PMWIN is designed to automatically determine this throughout the simulation. This would in turn result in the least effort for specification of input data (McDonald & Harbaugh, 1988).

4.4.3 Model calibration

In this study, the groundwater flow model was calibrated by trial-and-error method. The calibration targets were hydraulic head for pumping well 4 and the observation wells. The uncertain and assumed parameters, i.e. recharge via precipitation; infiltration rate via injection wells or creeks; and conductance of the river bed were adjusted to get a best fit. The hydraulic head value thus obtained by running the model with adjusted parameters were compared with the observed hydraulic heads. The model was calibrated against the observed hydraulic head from 11.11.2011 (*Table 4-3*). This was the day after the pumping test of pumping well 4 was stopped.

The summary statistics RMSE was used to interpret the calibration result. As suggested by literature (Anderson et al., 2015), an acceptable error of 0.165 m or less was chosen which is nearly 10 % of the difference between highest and lowest observed hydraulic heads.

Table 4-3: Observed hydraulic head values of wells

Wells	Observed hydraulic head (m)
Observation well 1	112.72
Observation well 2	113.83
Observation well 3	114.17
Observation well 4	114.04
Observation well 5	114.28
Observation well 6	114.18
Pumping well 4	112.63

The calibration started by changing one parameter at a time and estimating the RMSE values. At first, riverbed conductance was adjusted first to narrow down the error followed by precipitation and infiltration parameters. The conductance value was adjusted according to the hydraulic conductivity range of 10^{-7} to 10^{-3} m/s as assumed in the conceptual model, with the hydraulic conductivity increasing as the river flows downstream.

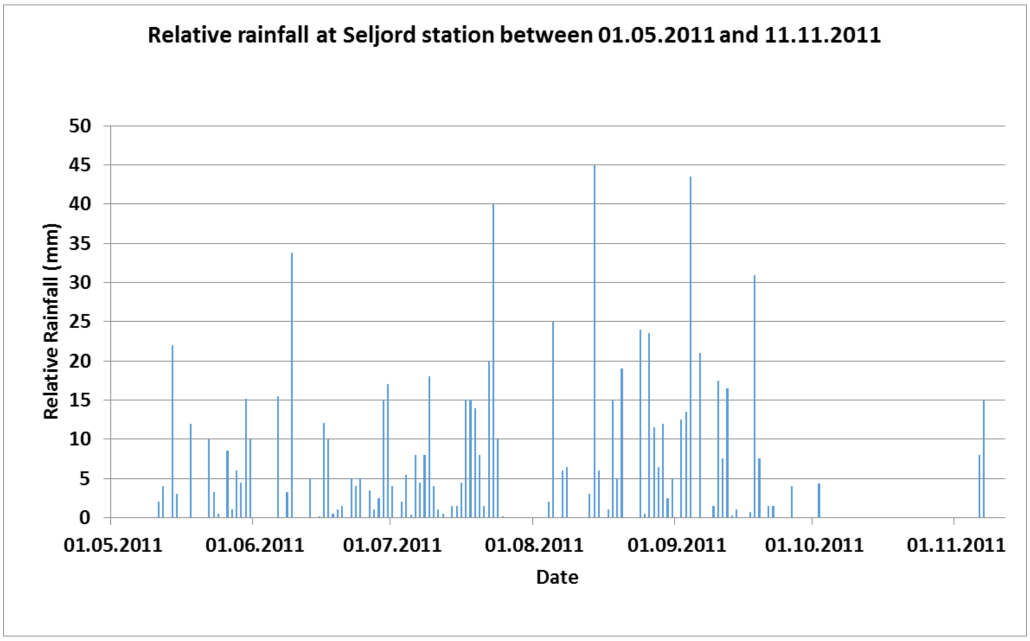

Figure 4-9: Relative rainfall at Seljord station between 01.05.2011 and 11.11.2011

The precipitation value was estimated according to the relative rainfall data in the Seljord station between 01.05.2011 and 11.11.2011 (*Figure 4-9*). The reason behind selecting Seljord station was the lack of weather station in Bø during the time period selected for calibration. In addition, the nearest weather station to Bø that suits the condition was Seljord station, because the weather station in Lifjell is at higher altitude, and that in Gvarv is at lower altitude. The rainfall data shows that there has been low rainfall during October and November; however, there was heavy rainfall in September. The total number of days with rainfall was 93. The highest rainfall of 45 mm was recorded on 14.08.2011.

4.5 Model visualization

In this study, the models are visualized in terms of hydraulic heads contours for groundwater flow and the advective transport of particle tracking to determine capture zones of the pumping wells.

4.5.1 Flow simulation

The hydraulic heads visualization in this study represents the water level and the flow of water through the aquifer when the wells were pumped. The hydraulic heads from PMWIN needed to be saved as surfer files (real world) supported by Notepad, which was then processed using MS Excel by importing data from surfer files in the form of XYZ-coordinates, where XY-coordinates present the geographical location and Z represent the hydraulic head. The excel file was then imported into ArcMap using data management tools in the Arctool box. Further processing in ArcMap included development of shape files to make Digital Terrain Model (DTM) and surface contours (*Figure 4-10*).

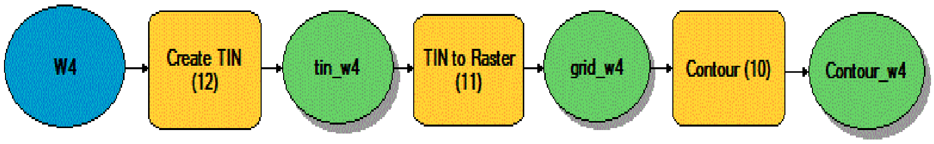

Figure 4-10: Model builder to make DTM and equipotential lines in ArcMap

4.5.2 Advective transport

The capture zones of pumping wells around the aquifer was simulated using advective transport method called PMPATH in PMWIN. The particle tracking method was used to calculate the groundwater flow paths (Chiang, 2005). This particle tracking process also helped to identify the possible flow pathway of the contaminants from any source in the aquifer.

In this study, backward particle tracking was used to determine the capture zones of the pumping wells. For determining the capture zones, the pumping well cell in the model was set as end of the flow and given particle values. The flow of the particle was then tracked backward to determine its start point thereby finding the capture zones of the pumping well as well as groundwater flow pathway.

In addition, forward particle tracking was used to predict the flow pathway of possible contaminant from the source. The probable contaminants for the Hagadrag aquifer assumed for simulation were chloride from road salting and chloride and manganese from the Herretjønn. For tracking chloride transport from the road, contaminant particles were placed alongside the road Rv.36 in the model area. Similarly, for the contaminants transport from Herretjønn, particles were placed on Herretjønn. The model was then run along with pumping from the well to trace the flow pathway of the contaminants, thereby determining the area where it ends.

The particle tracking output from PMWIN was saved as DXF files, which were converted to shape files in ArcMap for visualization and analysis.

5 Results

5.1 Calibration result

Even though, there was desire to estimate most of the aquifer parameters to represent the model close to the real situation. But due to the fact that complexity of calibration would increase with the increase in number of parameters to be estimated the parameters chosen for calibration were the ones that were assumed to be uncertain during the model development.

As mentioned earlier, the model in this study was calibrated using manual trial-and-error calibration to get a best fit and meet the benchmark value for error minimization using RMSE. A total number of three parameters were adjusted and included hydraulic conductance of the riverbed, precipitation and infiltration rate of injection wells. These were the most uncertain and assumed parameters while developing the model. The calibration results were compared with seven observed hydraulic heads; one for pumping well 4 and one each for six observed wells measured on 11.11.2011 (*Table 4-3*).

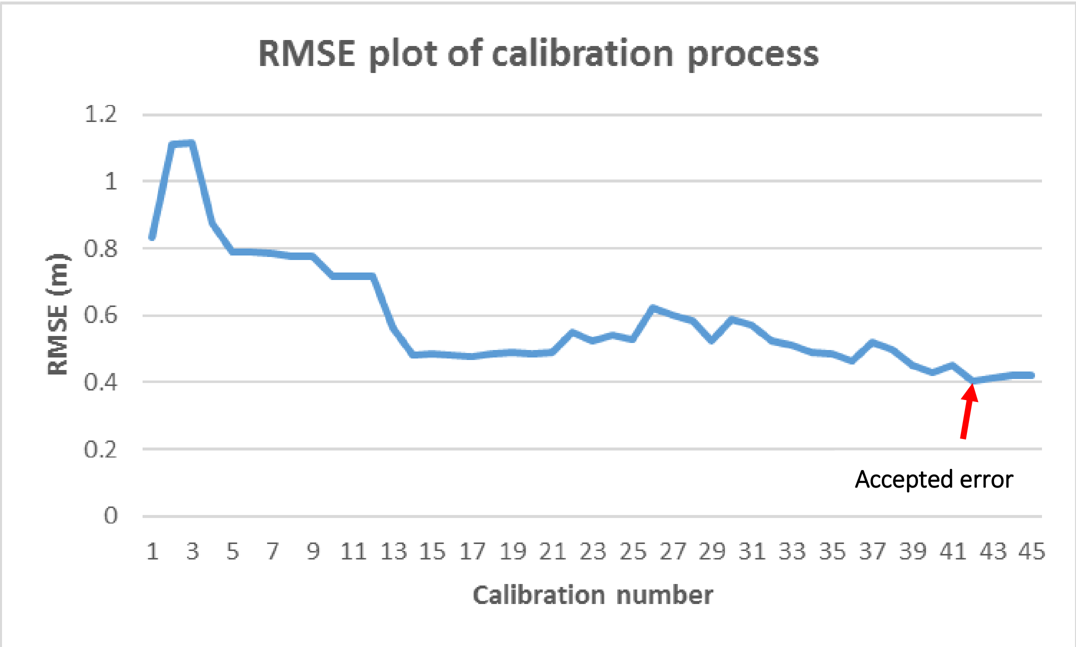

Figure 5-1: RMSE plot of calibration process

The acceptance of the calibration result was based on the optimization of the parameter that best suit the aquifer condition, rather than the quantitative evaluation of lowering the RMSE value to 10% of the difference between the highest and lowest observed hydraulic head. The parameters were calibrated to the value that best suited the aquifer condition based on the conceptual model. The calibration process was stopped once the RMSE value started increasing again, and the parameters seemed to be justified (*Figure 5-1*).

The RMSE value of the calibrated model of 0.402 m (*Appendix 4*) was considered as acceptable error. The acceptable error was 24.3% of the difference between the highest and lowest observed hydraulic heads. The estimated optimized parameters are presented in *Appendix 5*.

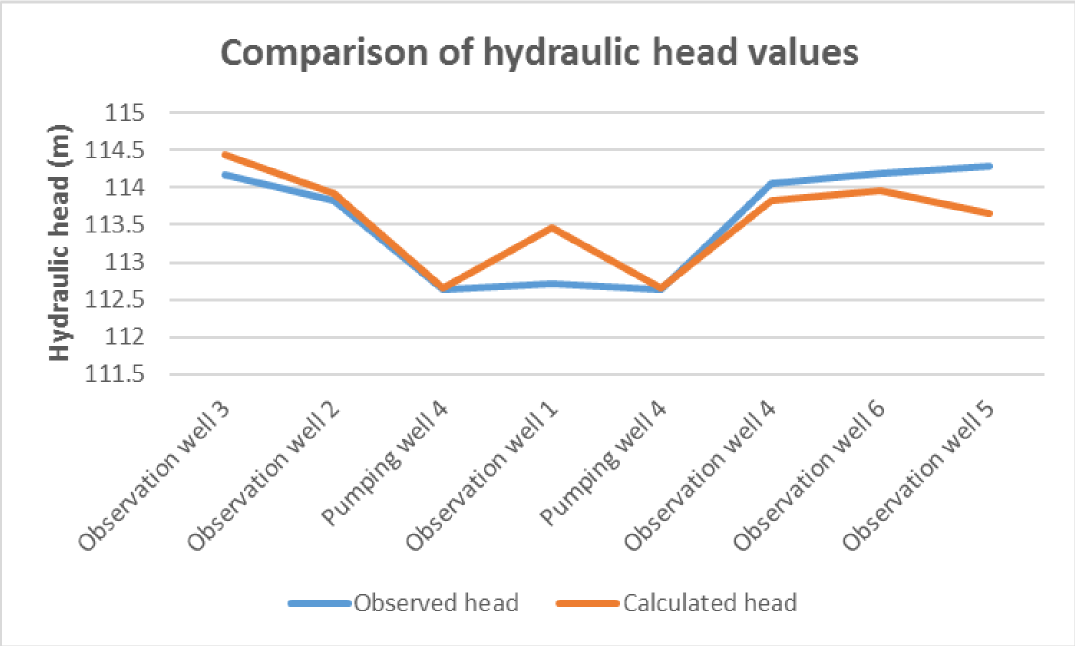

Figure 5-2: Comparison of observed and calculated head values

The hydraulic head values for observation wells 1 and 5 had largest deviation from the observed values of -0.7464 m and 0.6311 m respectively (*Figure 5-2*), whereas hydraulic heads of other wells were nearly close to the observed values with little deviation. The scatter diagram (*Figure 5-3*), shows how close the observed and calculated values are to the goodness of fit.

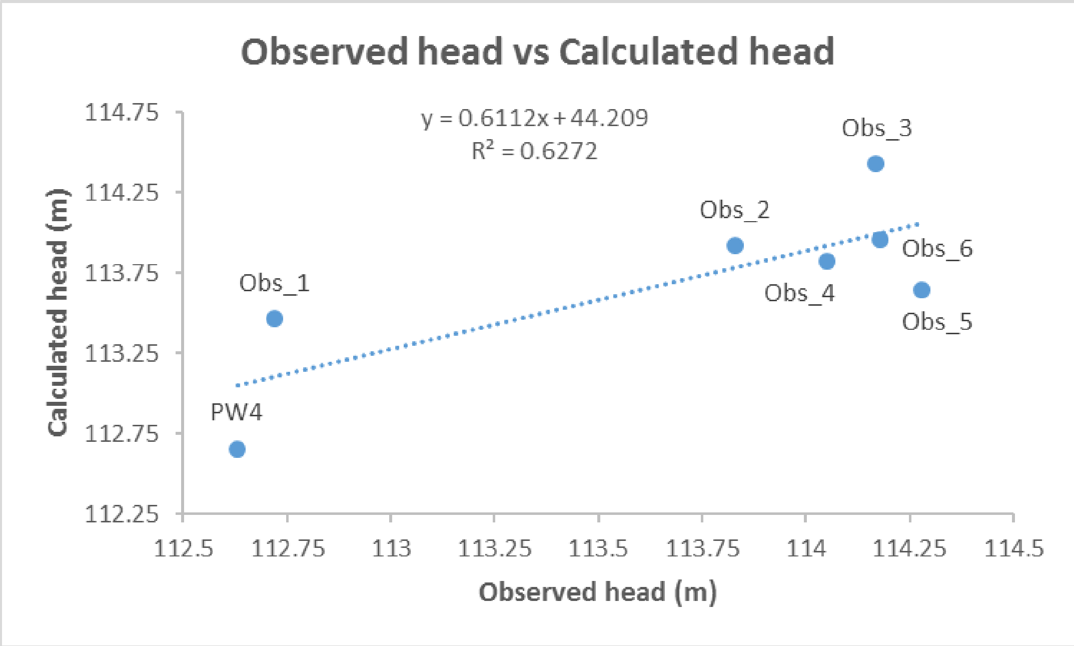

Figure 5-3: Scatterplot of observed head and calculated head

5.2 Capture zone simulation

The capture zone of the pumping wells were simulated by backward particle tracking in PMWIN. The water particles were defined at the wells as an end point and then tracked backwards to find the source, thereby showing the flow pathway.

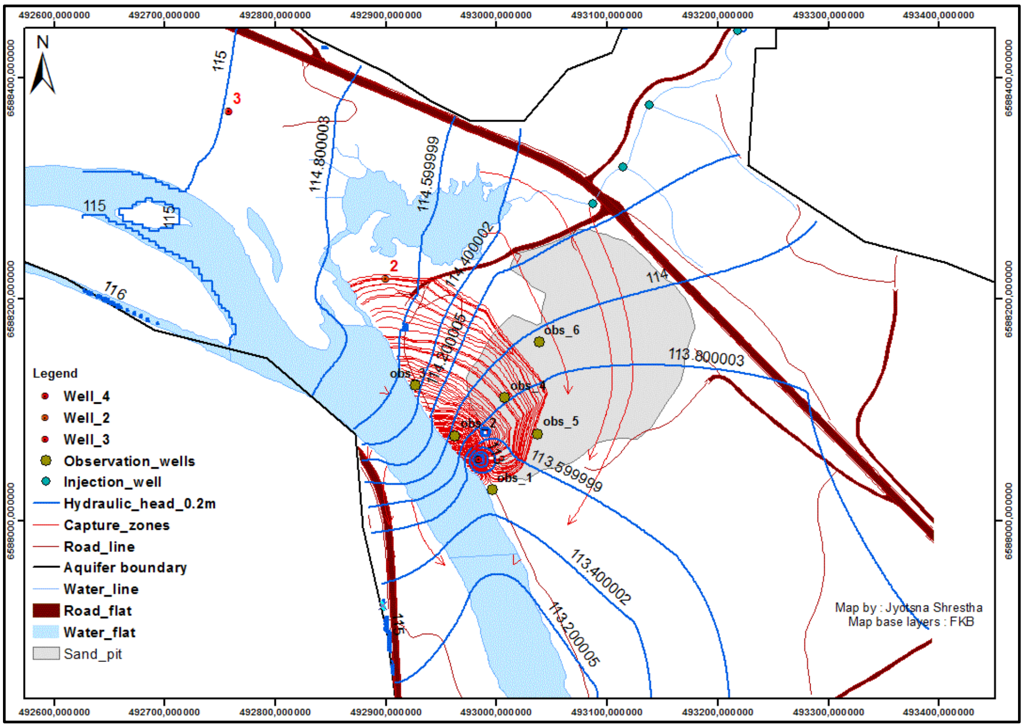

Figure 5-4: Simulated flow image of pumping well 4

The *figure 5-4* presents simulated flow direction of the water in the aquifer when pumping well 4 is pumped alone. The red arrows in the figure represent flow direction, whereas the dark blue lines represent hydraulic head contours. During the pumping of pumping well 4; the water in the aquifer flows from the northwest part of the model area towards the northeast and finally towards the Bø river in the south. The pumping well 4 drained water mostly from the Bø river area including the outlet of Herretjønn. In addition, water from Herretjønn seems to drain via gravel pit towards the downstream of the river.

The pumping of pumping well 2 and 4 (*Figure 5-5*) shows that water flows from the upstream of Bø river towards Herretjønn and from where the water further flows towards the river downstream. The pumping well 2 drains water mostly form Herretjønn and its outlet in the Bø river and from the Bø river, whereas the pumping well 4 drains water completely from the Bø river alone.

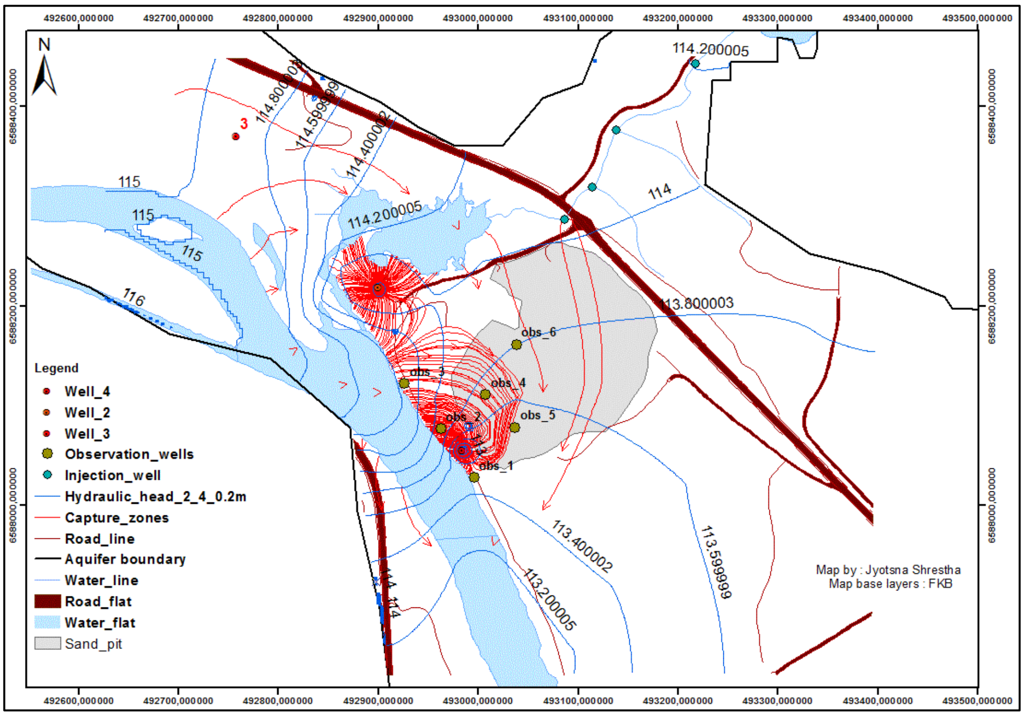

Figure 5-5: Simulated flow image of pumping wells 2 and 4

Similarly, the pumping of pumping well 3 and 4 (*Figure 5-6*) shows that pumping well 4 continues to drain water mostly from the Bø river and partially from the outlet of Herretjønn. The pumping well 3 withdraws water mostly from the river upstream and also from the Herretjønn. In addition, pumping well 3 drains water from the area nearby Hønsåa that passes close to the road Rv.36.

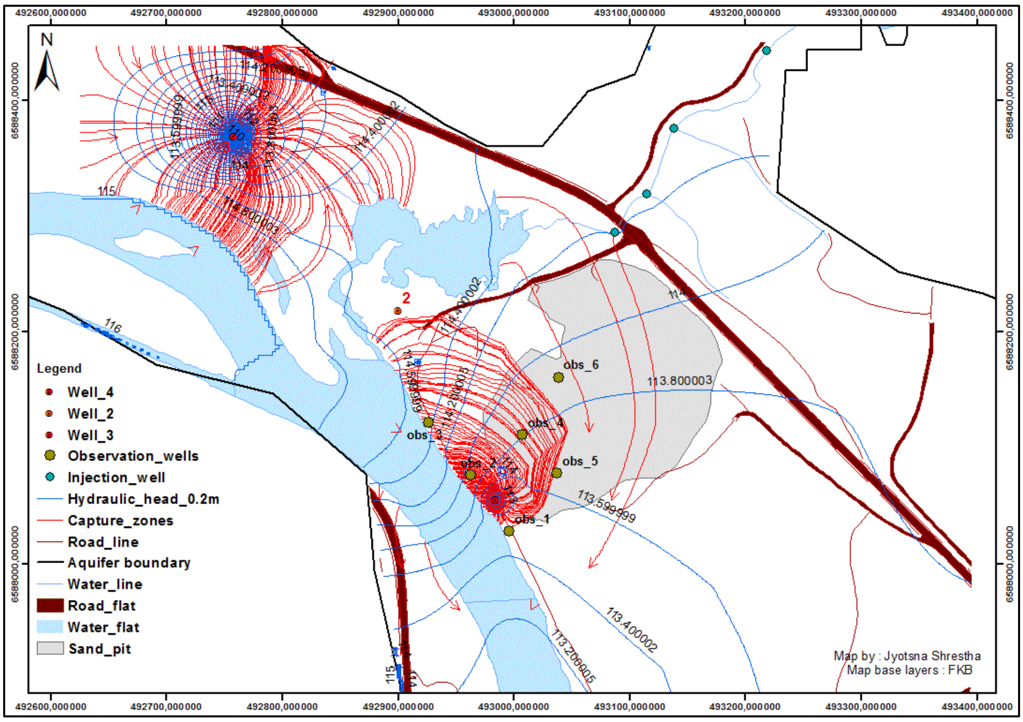

Figure 5-6: Simulated flow image of pumping wells 3 and 4

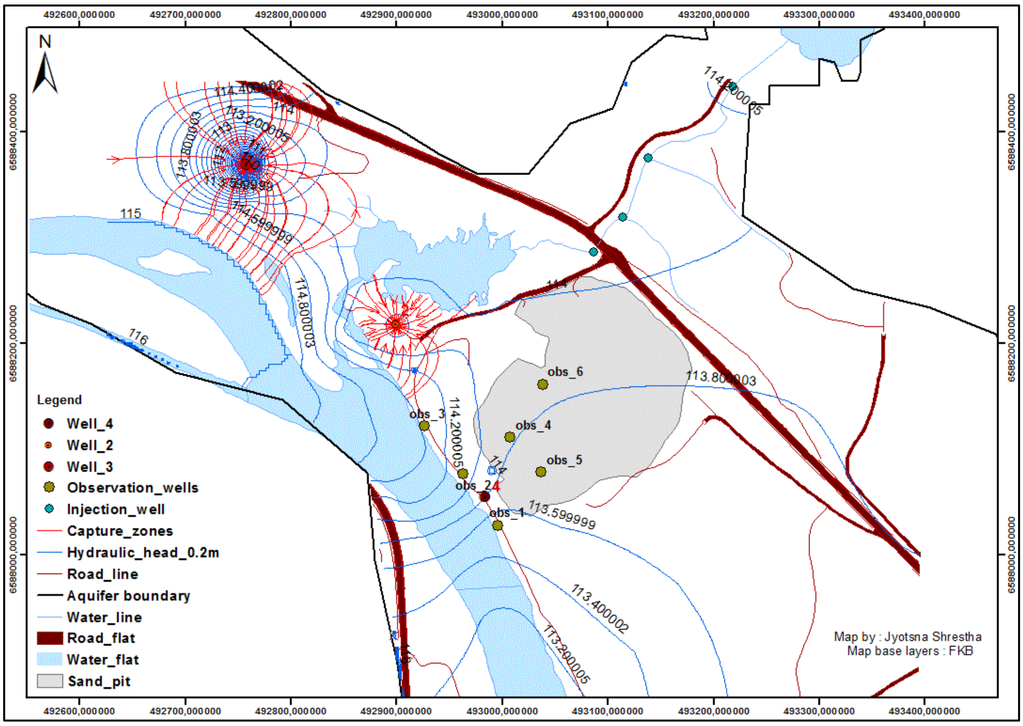

Figure 5-7: Simulated flow image of pumping wells 2 and 3

When wells 2 and 3 are pumped together (*Figure 5-7*), water from Herretjønn drains into pumping well 2 but not into the pumping well 3. However, pumping well 3 drains water from the river upstream and partially from the area nearby Hønsåa.

Looking back into time when pumping well 1 was functional, the flow simulation (*Figure 5-8*) shows that when both wells 1 and 4 are pumped together, the pumping well 1 drained water mostly from Herretjønn and partially from Bø river. However, water from Herretjønn drained also into pumping well 4 in addition to drainage from Bø river into the pumping well 4.

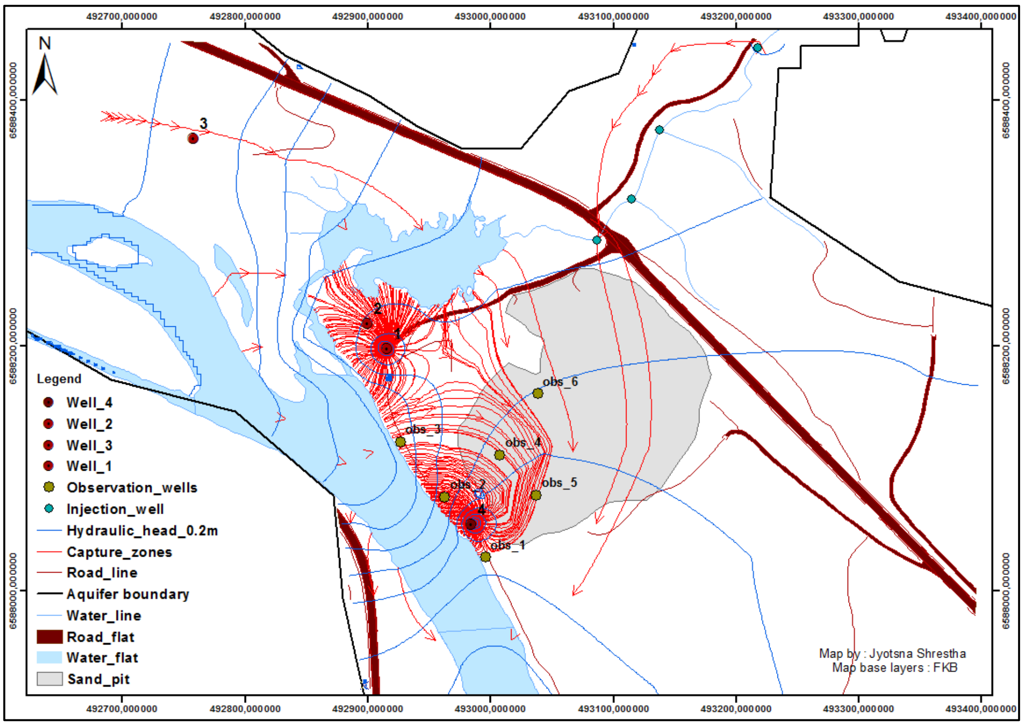

Figure 5-8: Simulated flow image of pumping wells 1 and 4

5.3 Contaminants transport pathway

The road Rv.36 that crosses the Hagadrag aquifer has been assumed as the source of chloride contamination for the aquifer, because of high salt use during winter to melt the snow. In addition, the high amount of manganese in the Herretjønn signals the exposure of manganese into the pumping wells. The model developed in this study was thus utilized to predict the contamination pathway via forward particle tracking.

5.3.1 Vulnerability from the road

The contaminant particles from the road seem to flow towards the river downstream bypassing the pumping wells when pumping well 4 is pumped alone (*Figure 5-9*). Similarly, when pumping wells 2 and 4 are pumped together (*Figure 5-10*), most of the contaminants bypass both the pumping wells and end into the river downstream, but a small amount of the contaminants seem to flow into Herretjønn from the upper road region.

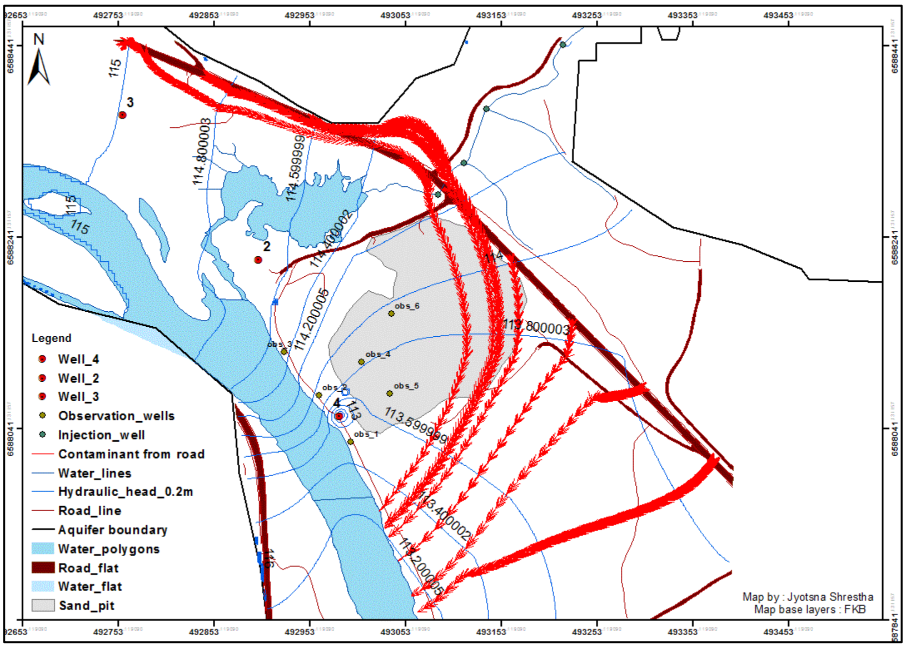

Figure 5-9: Flow of contaminants from road due to pumping of well 4

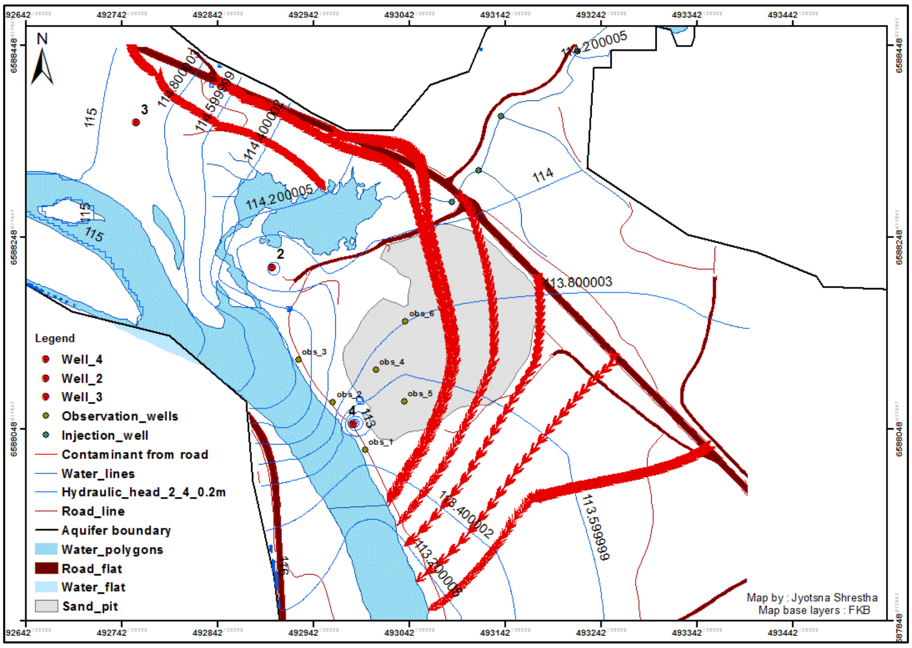

Figure 5-10: Flow of contaminants from road due to pumping of wells 2 and 4

The contaminants from the road seem to accumulate in the pumping well 3 when pumped together with either pumping well 2 or 4 (*Figure 5-11* and *5-12*).

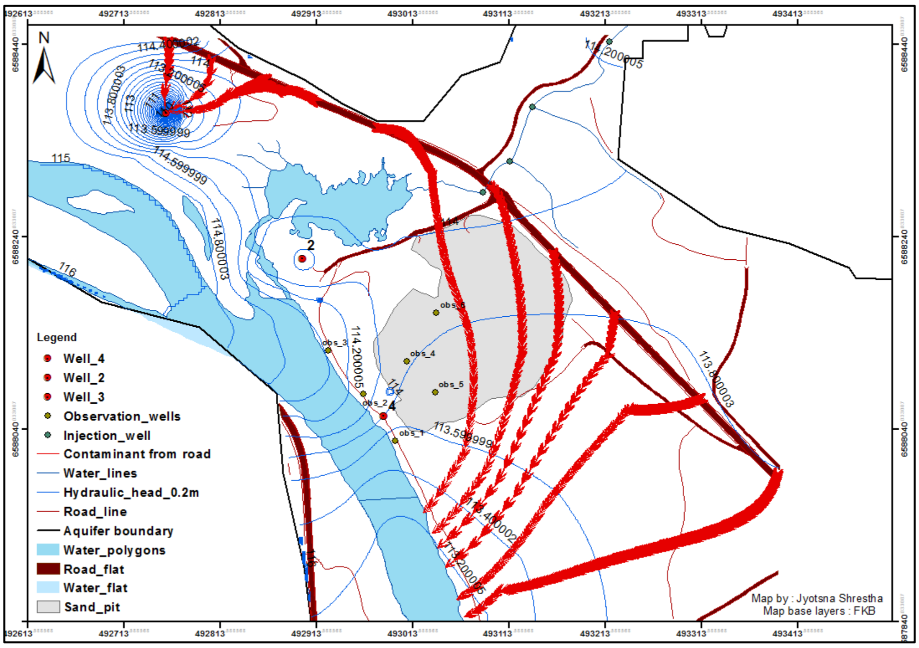

Figure 5-11: Flow of contaminants from road due to pumping of wells 2 and 3

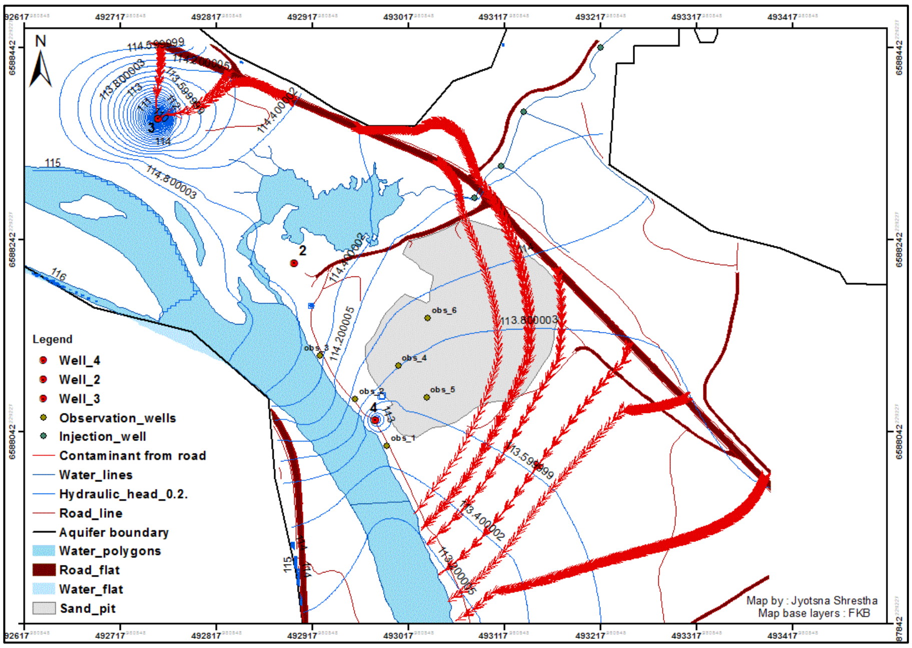

Figure 5-12: Flow of contaminants from road due to pumping of wells 3 and 4

5.3.2 Transport pathway from Herretjønn

Previous studies have identified Herretjønn as the reservoir of manganese and chloride and suggested that high concentration of these components in the pumping wells can be due to transport from Herretjønn to the pumping wells.

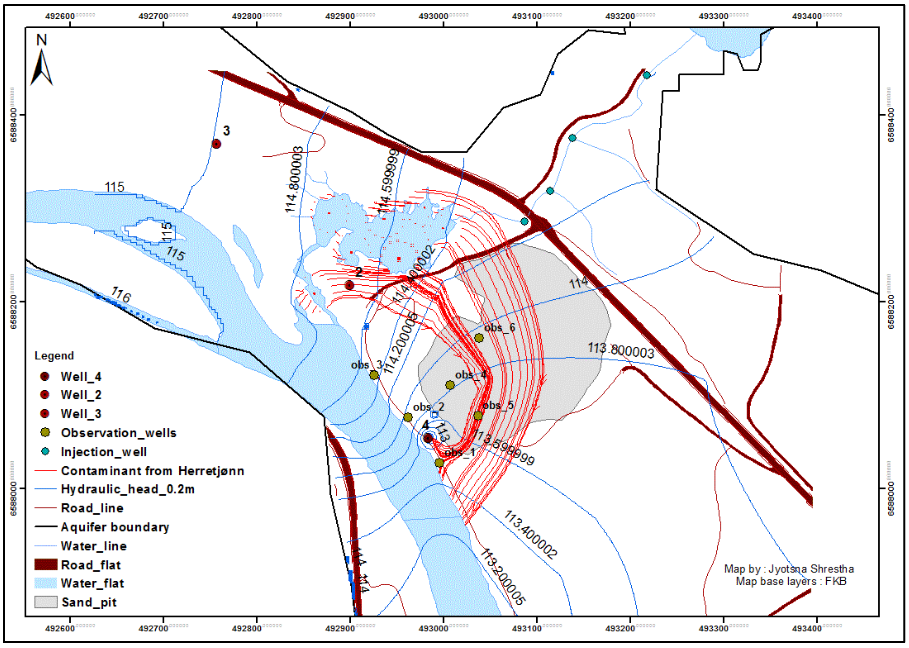

Figure 5-13: Flow of contaminants from Herretjønn due to pumping of well 4

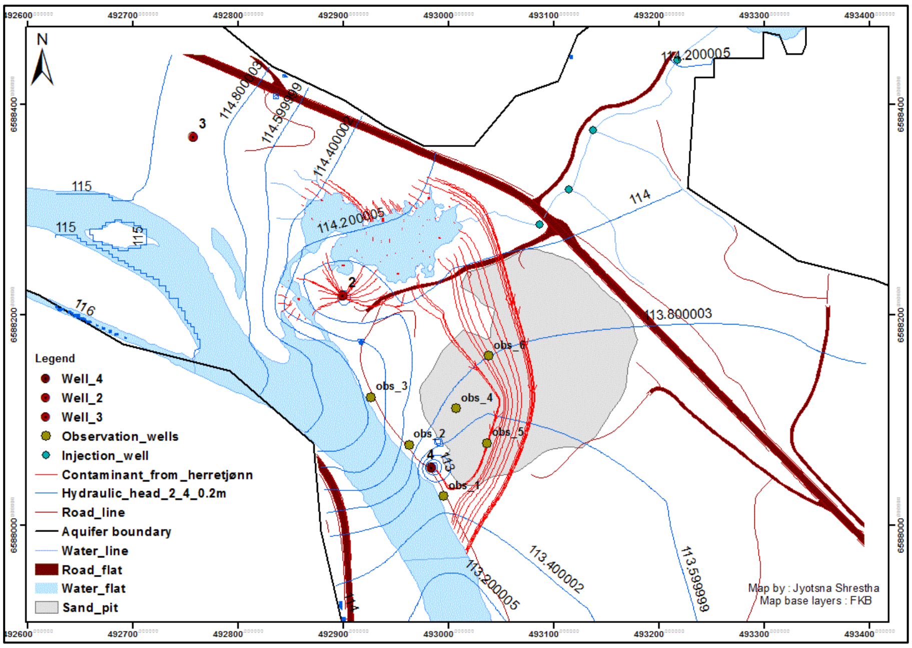

Figure 5-14: Flow of contaminants from Herretjønn due to pumping of wells 2 and 4

The contaminants particle seem to drain partially into the pumping well 4 from Herretjønn, when the pumping well 4 is pumped alone (*Figure 5-13*).

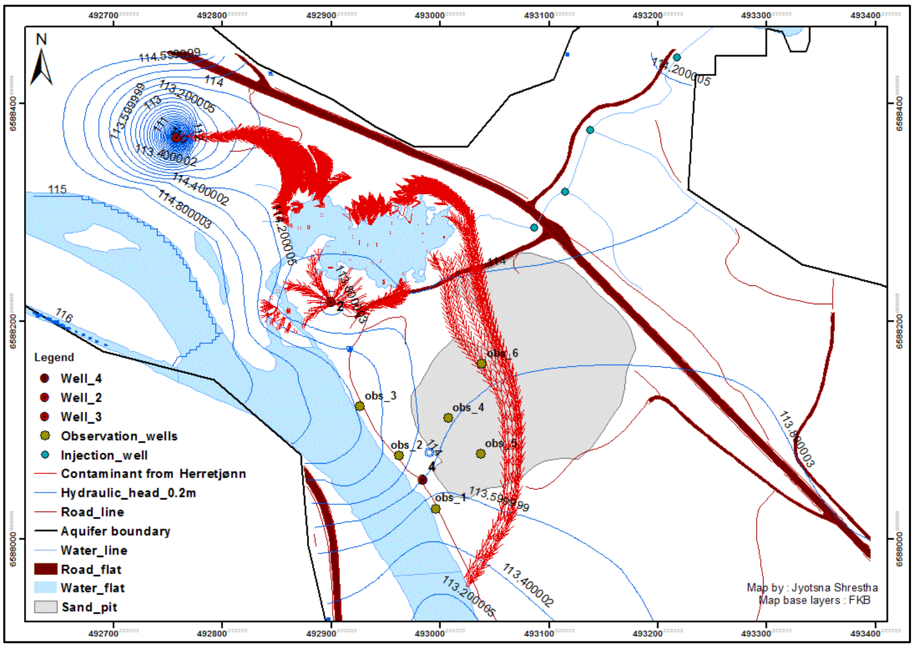

Figure 5-15 Flow of contaminants from Herretjønn due to pumping of wells 2 and 3

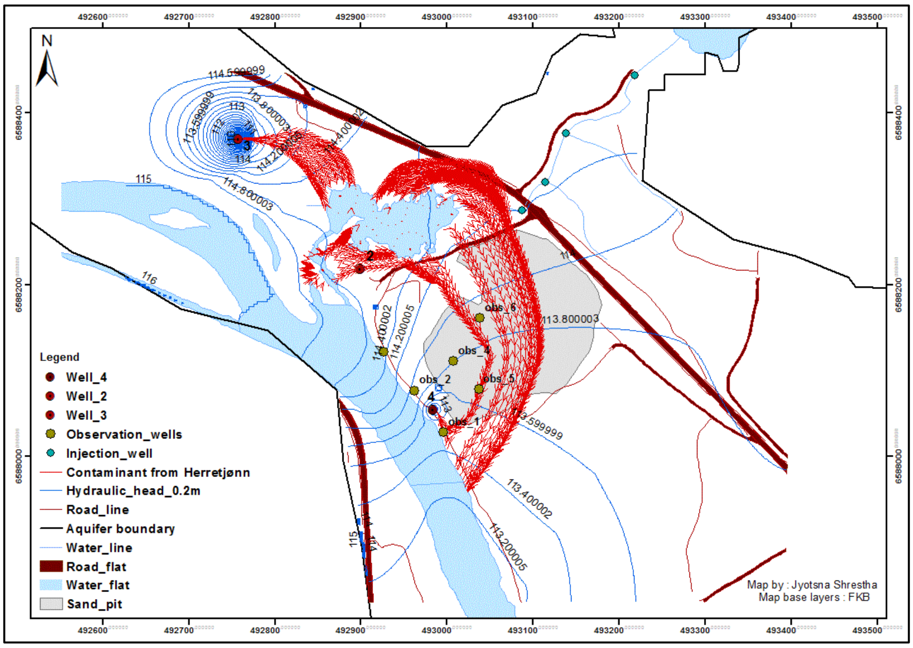

Figure 5-16: Flow of contaminants from Herretjønn due to pumping of wells 3 and 4

Similarly, when both pumping wells 2 and 4 are pumped together (*Figure 5-14*), contaminants from the Herretjønn drain into both these wells. Pumping of pumping wells 2 and 3 (*Figure 5-15*) show that huge amount of contaminants from Herretjønn flow into these wells; whereas pumping of wells 3 and 4 together (*Figure 5-16*), results in flow of high amount of contaminants into well 3 and comparatively small amount into well 4. However, huge amount of contaminants from Herretjønn flow directly into the river downstream in all these scenarios.

5.4 Water Budget

PMWIN calculates volumetric water budget of a particular boundary to determine flow in and out of the boundary (Chiang & Kinzelbach, 1998). The percentage discrepancy of the calibrated model in this study is zero, suggesting that the model equations have been correctly solved.

Table 5-1 Groundwater budget of calibrated model

Flow term	Inflow (m^3/day)	Outflow (m^3/day)
Constant head	117.698840	154.19081
Wells	969.408020	2756.160
Recharge	2503.76510	0
Head dependent boundaries	7604.11550	8284.2348
Sum	11194.987	11194.5860

According to the water budget of the calibrated model during pumping of well 4 (*Table 5-1*); comparatively high volume of water is leaked into the Bø river from the aquifer than the water inflow from the constant head and head dependent boundaries of the river during the calibrated period. This suggests that the seasonal recharge from May to November is the important inflow entering the aquifer. The injection wells are also another important infiltration source for the aquifer.

In order to understand the water inflow and outflow of the Bø river and Herretjønn, the river and Herretjønn were divided into sub-regions with the help of polygon input method (*Appendix 6*). The water budget of the sub-regions suggest that the inflow of water from the river is higher around the area of pumping well 4; and as the river progresses downstream the water from the aquifer leaks into the river. The water budget of the sub-regions justifies the water flow pathway shown in *figure 5-4* above.

6 Discussion

6.1 Reflection on modeling approach

As in every groundwater modeling process (*Figure 2-1*), this study started with identification of the problem statement and objectives of the study. The main purpose of this study was to simulate the groundwater flow patterns of Hagadrag aquifer. For this purpose, there was a need of a calibrated groundwater flow model that would also determine the capture zones of the pumping wells and also predict the possible pathway of contaminants like chloride and manganese transport in the aquifer. Thus, this study was designed to develop a flow model from the available data from previous studies in the study area. One important difference from the earlier models for this aquifer is the change of the boundary at Kupatjønn from prescribed head to prescribed flux expressed by four recharge wells. There were much better hydraulic conductivity and transmissivity values due to drilling of pumping well 4 and six observation wells based on grain size distribution curves for every meter (Aarnes, 2015).

The next step in the modeling process involved identification of various data sources related to geological, geophysical, hydrological and hydrogeochemical information about the Hagadrag aquifer to constitute a conceptual model. These data were collected from previous studies on the study site as well as national map data. In order to translate the conceptual model into numerical model, MODFLOW (McDonald & Harbaugh, 1988); a modular three dimensional finite difference groundwater flow model developed by the USGS was used as model code. The fact that MODFLOW is a widely used numerical code for groundwater modeling which can easily simulate the effects of wells, rivers, drains, head-dependent boundaries and recharge (Chiang, 2005) is the reason behind choosing MODFLOW as a model code for this study. Accordingly PMWIN was used a model processer in this study, which is based on MODFLOW code and is a graphical interface of MODFLOW in Microsoft Windows operating system. In addition, ArcMap was used as pre-processor and post-processor tool. The data type and data files of both ArcGIS and PMWIN appear to be well integrating with each other.

The use of GIS tool has been proved beneficial to explain the groundwater flow model in this study (Singh, 2014; Singha et al., 2016). The ArcMap tool helped both in the data processing step (Orzol & McGrath, 1992) as well as data visualization (Xu et al., 2011) as the last step in this study. One of the central use of ArcMap as a pre-processor in this study was to create Thiessen polygons for assigning transmissivity values in the model area. The transmissivity values of the area around the observation wells and pumping wells were extracted from the grain size distribution data from previous studies (Aarnes, 2015; Klempe, 2011; Trollsås et al., 2005). There were only few sampling points with field transmissivity data available. The transmissivity of the unknown regions in the model area needed to be interpolated based on these field data. Therefore, Thiessen polygon was chosen to be best alternative in this study because of its ability to use few sampling points from the nearest neighbor to interpolate the transmissivity values to the unknown regions of the model area (Zhu, 2016).

Even though, the development of small area model is not presented in this model, but development process of this small area model helped a lot to gain ideas and functioned as a conceptual model to develop extended area model later in the modeling process. This was a way of starting modeling with building simple model and then progressing it to a complex one (Hill, 2006, p. 787). The model presented in this study was not developed at once, rather the modeling process involved several amendments in both the conceptual model and numerical model, thereby requiring numerous calibration steps.

Initially, using PEST as an automatic calibration tool was thought to be beneficial and time-saving (Anderson et al., 2015) as there were several uncertain parameters to be calibrated in this study. However, the fact that automatic calibration tools require the number of parameters to be estimated be lower than the number of calibration targets made it difficult to implement automatic calibration in this study (Anderson et al., 2015; Martin & Frind, 1998). There were only 7 observed hydraulic head values as calibration targets against more than 13 parameters to be estimated such as transmissivity of the polygons, recharge, infiltration from injection wells and riverbed conductance. The error message that popped up while running PEST was neglected to see if the calibration results would be satisfactory. The PEST presented the calculated values of parameters that would best fit the calibration targets, but the parameter values were not justifiable in accordance to the aquifer properties as suggested by the conceptual model and field data.

The PEST method mostly adjusted transmissivity values in order to match the hydraulic heads from the field data. Even though transmissivity values used in the model were calculated directly from the field data and were most certain parameters among others; these values were also considered initially for calibration so that better fit could be obtained. However, the transmissivity estimated by PEST did not support the field values, indicating that the parameters were overestimated by the PEST to support observed hydraulic heads (Anderson et al., 2015). Similarly, other parameters like precipitation, infiltration from injection wells and riverbed conductance were underestimated, since these values were to some extent untouched by the PEST. The estimated values of these parameters were similar to those provided during the model development. Therefore, manual trial-and-error method was chosen for calibration of the model in the subsequent modeling process.

It is well known that the calibration of the model to develop a numerical model that is a duplicate of the real aquifer is a time-consuming process. The lack of data sets related to actual recharge and percolations increased the complexity of the calibration process in this study. To ease the calibration process, only uncertain parameters were adjusted during manual calibration and included hydraulic conductance of the riverbed, precipitation and infiltration rate of injection wells. The manual calibration process started with the estimation of riverbed conductance. The first few calibration results (*Figure 5-1*) show rapid change in RMSE due to change in riverbed conductance. After the RMSE values started to stabilize, precipitation and infiltration rate of injection wells were adjusted to further lower the error. The changes in RMSE values were not rapid as in the case of riverbed conductance, thus suggesting riverbed conductance as the most sensitive parameters among the three uncertain parameters under estimation.

The manual calibration method helped to understand the behavior of the model on the change in hydraulic heads with change in parameters that were estimated, thereby determining the most sensitive parameter in the model. Furthermore, the manual calibration method also gave a chance to go through the conceptual model and make changes to it, which would be somehow impossible with the automatic calibration method (Reilly & Harbaugh, 2004) because of possibility of obtaining parameters that would be either overestimated or underestimated than the actual aquifer parameters as observed in the initial calibration process in this study.

There were few times, when there was necessity to go back to the conceptual model and amend it to make the model as close to the real situation, thereby presenting an optimal parameter that best suited the Hagadrag aquifer. Initially, the Bø river was modelled in the river package, but during calibration, it appeared that the infiltration from part of the river functions as general head boundaries. Being the crucial step in modeling process, proper consideration were required to define the boundary condition (Franke et al., 1987), as it highly influences the flow directions of the model (Anderson et al., 2015). Therefore, the conceptual model was revisited and the river was divided in two parts, the upstream being constant head boundaries, and the downstream behaving as General head boundary (Anderson et al., 2015).

The calibration result was estimated with RMSE as a summary statistics. The target of the calibration was to minimize the error to a minimum as possible. After numerous trial-and-error calibrations, the RMSE could not be reduced to 10 % or less to the range of observed head values. Therefore, subjective assessment of the calibrated parameters were made to end the calibration process (Anderson et al., 2015). It has been further discussed that the adequacy of the numerical model developed on the basis of well justified conceptual model with minor adjustments are considered to be better than the models developed with minimal error and over calibrated parameters (Reilly & Harbaugh, 2004).

The calibrated groundwater flow model of Hagadrag aquifer has been further utilized to simulate the groundwater flow pattern in the aquifer due to pumping. The simulations show that the location of a well in accordance to river bends and distance from river determines the flow pattern. This model also forms the basis for any future prediction related to contamination transport within the aquifer system from the nearby anthropological sources (Jyrkama et al., 2002; Singh, 2014).

6.2 Flow pattern in Hagadrag aquifer

Hagadrag aquifer is the important source of drinking water for the residents of Bø municipality. The water budget and capture zones show that the Bø river is biggest source for water infiltration into the aquifer. All the pumping wells drain water from the Bø river as a major source of recharge into the aquifer. In addition, the pumping wells also drain water from Herretjønn and its outlet into the Bø river. Therefore, presence of contaminants in river upstream and Herretjønn can directly affect the water quality (Zaporozec, 1981).

However, the water budget suggests that precipitation also plays a major role for the water balance between the aquifer and the surface water (Sophocleous, 2002). During the period with higher rainfall, the water from the aquifer seem to leak into the river. The infiltration from the Bø river occur mostly from the river beds around the pumping wells whereas leakage from the aquifer mostly occur in the river downstream towards Herrefoss.

Due to minimal evaporation during the calibration period because of fall period, most of the rainfall occurred in the time period might have infiltrated into the ground, thereby increasing the groundwater level and allowing the discharge of water into the Bø river. The findings from the flow simulation and water budget suggest that Bø river acts as both source of recharge to and discharge from the aquifer (Alley et al., 1999). The direction of flow between the river and aquifer depends on the amount of precipitation that may vary from season to season or climatic condition; and the volume of water pumped out of aquifer. This suggests that during summer season when the water extraction is higher due to increased water use in Sommarland, the Bø river and the outlet of Herretjønn acts as a major recharge source for the aquifer. Because of this good interaction between the Bø river, outlet of Herretjønn and Hagadrag aquifer, continuous monitoring of the Bø river to minimize contamination sources is vital for the water quality monitoring of the aquifer (Sophocleous, 2002).

6.3 Contamination threat to Hagadrag aquifer

As in most aquifers of Norway (NGU, 2015b), the Hagadrag aquifer is dominated by glaciofluvial and fluvial deposits comprising of well-sorted sand and gravels. These soil sediments are highly permeable and allow easy infiltration of water through it. The water extracted from the Hagadrag aquifer is considered to be of superior quality for drinking purposes. Since Hagadrag aquifer is dominated by permeable soil deposits, the water extracted from such deposits generally have better chemical and physical properties than the water extracted from the wells situated in the bedrock (NGU, 2015b). The infiltration of water through the permeable deposits allows series of natural cleaning and chemical exchange process thereby making the infiltrating water free from chemical impurities.

However, the high manganese concentration in Herretjønn can be seen as threat to the water quality of the aquifer. Similarly, the flow of contaminant particles from the road due to road salting during winter can be a source of chloride contamination in the aquifer. Even though previous studies have shown that the concentration of such contaminants are within the acceptance limit of the national standard currently (Kalauz, 2014; Kraft, 2011; Solli, 2016), but continuous deposition of contaminants in the aquifer might pose a big risk in near future. The contaminants like manganese and chloride (Kalauz, 2014; Ramberg, 2009), which in present are mostly located on the deeper level of the pumping wells and Herretjønn might become soluble under favorable physical and chemical conditions and may deteriorate the water quality.

The assumption in these previous studies was that chloride from the road salt travelled directly towards the pumping wells. In contrast, the contaminants transport pathway from the model simulation in this study shows an interesting pathway. Most of the particles from the road nearby pumping wells 2 and 4 travel towards the river downstream thereby bypassing these pumping wells. However, the contaminants from the upper part of the road towards Seljord accumulate mostly in Herretjønn when pumping well 2 is pumped together with pumping well 4. In addition, huge amount of road contaminants enter into pumping well 3 when pumped together with either 2 or 4. The simulation results comply with the result from the previous study (Kalauz, 2014), in which Herretjønn was suggested as a storage of chloride having higher chloride concentration in deep water samples from 3 m and 7 m depth (Ramberg, 2009).

The further flow transport of particle from Herretjønn indicates that contaminants that accumulate in Herretjønn can easily drain into all the pumping wells indicating that chloride concentration in pumping wells is not due to direct flow of chloride into the pumping wells, but due to the flow of particles from Herretjønn towards the wells. This further justifies the high concentration of manganese in pumping well 2 and 4, because these wells extract water from Herretjønn in addition to infiltration from Bø river. This also indicates that pumping well 2 is more vulnerable to degradation by contamination than pumping wells 3 and 4 because pumping well 2 drains water much from Herretjønn. Additionally, pumping well 2 lies in the close proximity of the major contamination source suspect, i.e. the Herretjønn than the other pumping wells. Thus, the time required for infiltration of water from Herretjønn to pumping wells 3 and 4 is relatively longer than the time required for pumping well 2, thereby reducing the effects of contamination in the former two wells (Belk, 1994).

From the groundwater flow and contamination transport pathway in this study, it can be concluded that the pumping well 4 is the safest among the three pumping wells, because it drains water mostly from Bø river and comparatively lesser volume from Herretjønn. In addition, pumping well 4 appears to be unaffected by contamination from the road sources. However, it is suggested that continuous monitoring of all these wells should be done.

6.4 Further recommendations

The numerical model of Hagadrag aquifer presented in this study was developed with retrospective field data. In addition, a single layer model was developed due to time constrain. Therefore, it is recommended that a multi-layer model with recent field data related to precipitation and information regarding infiltration via creeks can be helpful for better predictions and monitoring of the aquifer. For further model extension, model area can be increased to identify safer areas to drill probable pumping wells for future demands of increasing water usage of Bø municipality. ArcMap has been very helpful in this study both for preparation of data and to visualize the model developed in PMWIN. Thus, any future works for groundwater flow modeling should make use of GIS tools in addition to the modeling software.

7 Conclusion

The Hagadrag aquifer is the major source of drinking water for Bø municipality. The water requirement is fulfilled by pumping three wells at regular intervals. As the area around the aquifer is vulnerable to contamination because of anthropogenic activities, it is necessary to regularly monitor the groundwater quality. One of the methods to monitor groundwater quality is to use groundwater flow model. The numerical model of Hagadrag aquifer developed in this study has helped to identify the flow pattern of water in the aquifer as well as predict the advective transport of possible contaminants.

The modeling process followed a sequential groundwater modeling approach i.e. identification of the objective of the study, building a conceptual model, selection of model code, translation of conceptual model into numerical model, model calibration and result prediction. Being the backbone of the modeling process, much time was utilized for building a conceptual model that represented the real aquifer system. The model processor PMWIN has been very useful to graphically visualize the flow pathway. The use of ArcMap as a GIS tool to process the data for modeling and visualizing the model developed in PMWIN has been justified. Therefore, it is highly recommended to integrate GIS tool for groundwater modeling in future research works. Even though PEST as an automatic calibration tool was used initially to calibrate the model, but the results of calibration were not satisfactory because of higher number of parameters to be estimated than the calibration targets. Therefore, the model was calibrated manually to estimate riverbed conductance, precipitation and infiltration rate of injection wells. The transmissivity values were obtained from the field data and were thus not included for manual calibration. Among the calibrated parameters, riverbed conductance was the most sensitive parameter. The manual trial-and-error calibration method helped to better understand the behavior of model due to change in parameters thereby allowing modification of the conceptual model. The RMSE value of the calibrated model was 0.402 m; which is 24.3% of the difference between the highest and lowest observed hydraulic heads. The calibration of the model was not only focused on quantitative measure of RMSE, but also on the appropriateness of the estimated parameter values that comply with the conceptual model.

The groundwater flow patterns show that the flow of water in the aquifer is determined by the location of a well in accordance to the river bends and distance from the river. The findings from this study suggest that any contamination to the Bø river upstream and Herretjønn can be a big threat to the aquifer, as these two are the major sources of water infiltrating into the aquifer. The pumping wells 3 and 4 capture water mostly from Bø river; whereas the pumping well 2 captures water mostly from Herretjønn as it lies close to it. However, the volume of water infiltrated from the surface water resources into the Hagadrag aquifer depends mostly on the precipitation and volume of water extracted from the pumping wells.

Even though, the water from the aquifer is considered to be of good quality as per today, but the presence of chloride and manganese in the pumping wells and Herretjønn can be seen as a major threat in the long run. The particle tracking suggests that the flow of contaminant like chloride due to road salting is not directly from the road to the pumping wells 2 and 4. Rather, the contaminants transport via water transport from Herretjønn as huge amount of chloride enters into the Herretjønn from the upper part of the road and the rivulets from Kupatjønn to Herretjønn that crosses the road. However, the pumping well 3 gets chloride directly from the road as it lies near to the road Rv.36. It further suggests that higher the infiltration of water from Herretjønn into the aquifer, higher will be the chances of contamination. However, better predictions can be made with the further development in this numerical model via recent field data.

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Appendices

Appendix 1: Watershed map generated in NEVINA database

Lavvannskart

Vassdragsnr.:	016.CA5
Kommune:	Bø
Fylke:	Telemark
Vassdrag:	BØELVA

Vannføringsindeks, se merknader		
Middelvannføring (61-90)	10.2	l/(s*km²)
Alminnelig lavvannføring		l/(s*km²)
5-persentil (hele året)		l/(s*km²)
5-persentil (1/5-30/9)		l/(s*km²)
5-persentil (1/10-30/4)		l/(s*km²)
Base flow	-999.0	l/(s*km²)
BFI		

Klima		
Klimaregion		Sor
Årsnedbør	999	mm
Sommernedbør	483	mm
Vinternedbør	516	mm
Årstemperatur	2.7	°C
Sommertemperatur	10.0	°C
Vintertemperatur	-2.6	°C
Temperatur Juli	12.5	°C
Temperatur August	12.2	°C

Feltparametere	
Areal (A)	1.1 km²
Effektiv sjø (S_{eff})	0.4 %
Elvelengde (E_L)	0.4 km
Elvegradient (E_G)	17.1 m/km
$Elvegradient_{1085}$ (G_{1085})	9.1 m/km
Feltlengde(F_L)	1.5 km
H_{min}	125 moh.
H_{10}	136 moh.
H_{20}	147 moh.
H_{30}	168 moh.
H_{40}	185 moh.
H_{50}	220 moh.
H_{60}	261 moh.
H_{70}	317 moh.
H_{80}	380 moh.
H_{90}	464 moh.
H_{max}	574 moh.
Bre	0.0 %
Dyrket mark	0.0 %
Myr	0.0 %
Sjø	0.0 %
Skog	98.1 %
Snaufjell	0.0 %
Urban	0.0 %

1) Verdien er editert

Norges vassdrags- og energidirektorat
NVE

Kartbakgrunn: Statens Kartverk
Kartdatum: EUREF89 WGS84
Projeksjon: UTM 33N

Nedbørfeltgrenser, feltparametere og vannføringsindekser er automatisk generert og kan inneholde feil. Resultatene må kvalitetssikres.

Det er generelt stor usikkerhet i beregninger av lavvannsindekser. Resultatene bør verifiseres mot egne observasjoner eller sammenlignbare målestasjoner.

I nedbørfelt med høy breprosent eller stor innsjøprosent vil tørrværsavrenning (baseflow) ha store bidrag fra disse lagringsmagasinene.

Calculation of infiltration rate per injection well:

Area of watershed (A) = 1.1 km^2

Streamflow in the watershed (Middelvannsføring) = 10.2 l / (s* km^2)

Therefore,

Total infiltration in the watershed (Ti) = Middelvannsføring * A

= 10.2 * 1.1 l / s

= 11.22 l / s

= 11.22 * 60 * 60 * 24 l / day

= 969408 l /day

= 969.408 m^3 / day

Infiltration per injection well = Ti / 8

= 969.408 (m^3 / day) / 8

= 121.176 m^3 / day

Appendix 2: Transmissivity values of study area

Polygons	Location of wells	Transmissivity (m^2/s)	Transmissivity (m^2/day)
1	Pumping well 3	0.001945	168.048000
2		0.0106	915.840000
3		0.004543	392.515200
4		0.01529	1321.056000
5		0.009151	790.646400
6		0.001018	87.955200
7		0.009323	805.507200
8		0.025945	2241.648000
9		0.015907	1374.364800
10	Pumping well 2	0.053714	4640.889600
11		0.053714	4640.889600
12		0.014541	1256.342400
13		0.006283	542.851200
14		0.006986	603.590400
15		0.02064	1783.296000
16	Observation well 3	0.007818	675.475200
17	Observation well 2	0.027237	2353.276800
18	Observation well 4	0.012255	1058.832000
19	Observation well 6	0.037312	3223.756800
20	Observation well 5	0.155874	13467.513600
21	Observation well 1	0.054352	4696.012800
22		0.011975	1034.640000
23	Pumping well 4	0.012	1036.80000

Appendix 3: Parameters for General Head Boundary (GHB) package

Polygon	Hydraulic conductivity (K_{riv}) (m/day)	River length (l) (m)	River width (W_{riv}) (m)	Riverbed (M_{riv}) (m)	Riverbed conductance (C_{riv}) (m^2/day)	Head in the river (m)
1	0.00864	2	45.33	1	0.7833024	115
2	0.00864	2	87.74	0.5	3.0322944	115
3	0.00864	2	63.19	0.5	2.1838464	114.86
4	0.00864	2	54.69	0.5	1.8900864	114.5
5	0.00864	2	59.67	0.5	2.0621952	114
6	0.00864	2	58.05	0.5	2.006208	113.2
7	0.00864	2	62.1	0.5	2.146176	113

$$C_{riv} = \frac{K_{riv} \times l \times W_{riv}}{M_{riv}}$$

Appendix 4: Calculation of RMSE from the calibration result

Wells	Observed head (h_m) (m)	Calculated head (h_s) (m)	(h_m-h_s)	$(h_m-h_s)^2$
Observation well 3	114.17	114.4296	-0.2596	0.067392
Observation well 2	113.83	113.9205	-0.0905	0.00819
Pumping well 4	112.63	112.6576	-0.0276	0.000762
Observation well 1	112.72	113.4664	-0.7464	0.557113
Observation well 4	114.05	113.827	0.223	0.049729
Observation well 6	114.18	113.9554	0.2246	0.050445
Observation well 5	114.28	113.6489	0.6311	0.398287
Sum			-0.0454	1.131919
RMSE			**0.402**	

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i^2}$$

Appendix 5: Optimized parameters after model calibration

Parameter name		Initial value	Calibrated value
Hydraulic conductance of river bed (m^2/d)	Polygon 1	0.7833024	0.7833024
	Polygon 2	3.032295	3.032295
	Polygon 3	1.566605	1.566605
	Polygon 4	2.183846	21.83846
	Polygon 5	1.890086	18.90086
	Polygon 6	2.062195	20.62195
	Polygon 7	2.006208	20.06208
Recharge (m/d)		0.001095	.00729
Infiltration rate of each injection well (m^3/d)		121.176	242.352

Appendix 6: Water budget of sub-regions over the entire model

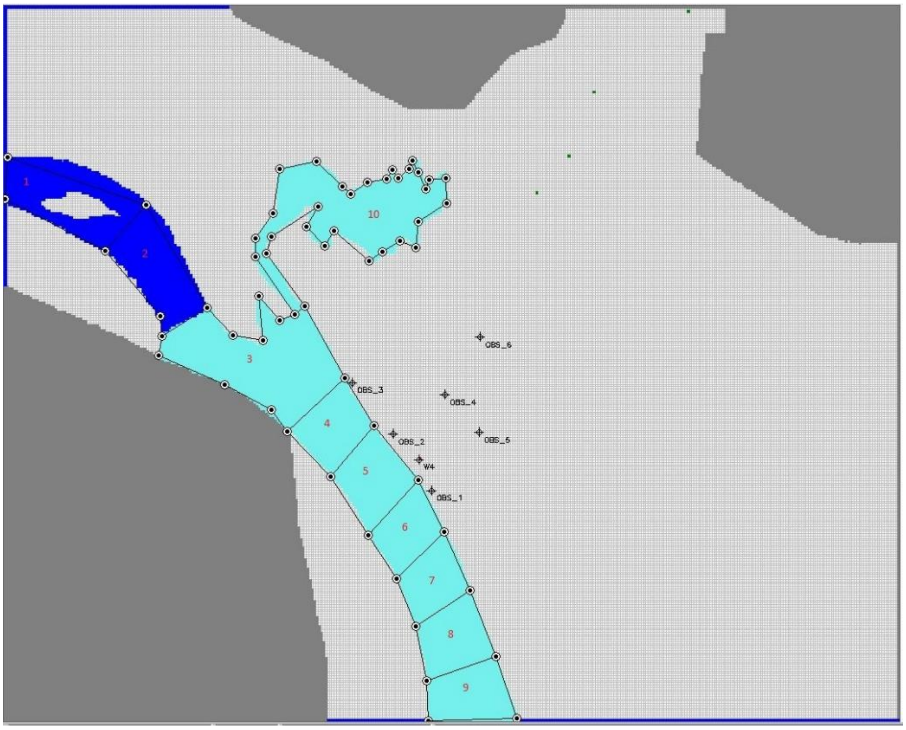

Figure 7-1: Sub-region of the Bø-river and Herretjønn for water budget calculation

Table 7-1: Water budget of sub-region 1

FLOW TERM	IN (m³/day)	OUT (m³/day)	IN-OUT (m³/day)
STORAGE	0.000000	0.000000	0.000000
CONSTANT HEAD	0.000000	17.598149	-17.598149
HORIZ. EXCHANGE	10.328568	0.000000	10.328568
EXCHANGE (UPPER)	0.000000	0.000000	0.000000
EXCHANGE (LOWER)	0.000000	0.000000	0.000000
WELLS	0.000000	0.000000	0.000000
DRAINS	0.000000	0.000000	0.000000
RECHARGE	7.260840	0.000000	7.260840
ET	0.000000	0.000000	0.000000
RIVER LEAKAGE	0.000000	0.000000	0.000000
HEAD DEP BOUNDS	0.000000	0.000000	0.000000
STREAM LEAKAGE	0.000000	0.000000	0.000000
INTERBED STORAGE	0.000000	0.000000	0.000000
RESERV. LEAKAGE	0.000000	0.000000	0.000000
SUM OF THE REGION	17.589408	17.598149	-0.008741
DISCREPANCY [%]	-0.05		

Table 7-2: Water budget of sub-region 2

FLOW TERM	IN (m^3/day)	OUT (m^3/day)	IN-OUT (m^3/day)
STORAGE	0.000000	0.000000	0.000000
CONSTANT HEAD	8.301843	20.765210	-12.463367
HORIZ. EXCHANGE	20.811502	6.411368	14.400134
EXCHANGE (UPPER)	0.000000	0.000000	0.000000
EXCHANGE (LOWER)	0.000000	0.000000	0.000000
WELLS	0.000000	0.000000	0.000000
DRAINS	0.000000	0.000000	0.000000
RECHARGE	1.137240	0.000000	1.137240
ET	0.000000	0.000000	0.000000
RIVER LEAKAGE	0.000000	0.000000	0.000000
HEAD DEP BOUNDS	0.000000	3.076732	-3.076732
STREAM LEAKAGE	0.000000	0.000000	0.000000
INTERBED STORAGE	0.000000	0.000000	0.000000
RESERV. LEAKAGE	0.000000	0.000000	0.000000
SUM OF THE REGION	30.250584	30.253309	-0.002725
DISCREPANCY [%]	-0.01		

Table 7-3: Water budget of sub-region 3

FLOW TERM	IN (m^3/day)	OUT (m^3/day)	IN-OUT (m^3/day)
STORAGE	0.000000	0.000000	0.000000
CONSTANT HEAD	6.586006	0.000000	6.586006
HORIZ. EXCHANGE	177.540040	917.790350	-740.250310
EXCHANGE (UPPER)	0.000000	0.000000	0.000000
EXCHANGE (LOWER)	0.000000	0.000000	0.000000
WELLS	0.000000	0.000000	0.000000
DRAINS	0.000000	0.000000	0.000000
RECHARGE	66.863881	0.000000	66.863881
ET	0.000000	0.000000	0.000000
RIVER LEAKAGE	0.000000	0.000000	0.000000
HEAD DEP BOUNDS	697.752340	30.973996	666.778350
STREAM LEAKAGE	0.000000	0.000000	0.000000
INTERBED STORAGE	0.000000	0.000000	0.000000
RESERV. LEAKAGE	0.000000	0.000000	0.000000
SUM OF THE REGION	948.742270	948.764350	-0.022078
DISCREPANCY [%]	0		

Table 7-4: Water budget of sub-region 4

FLOW TERM	IN (m^3/day)	OUT (m^3/day)	IN-OUT (m^3/day)
STORAGE	0.000000	0.000000	0.000000
CONSTANT HEAD	0.000000	0.000000	0.000000
HORIZ. EXCHANGE	373.222070	2346.332900	-1973.110800
EXCHANGE (UPPER)	0.000000	0.000000	0.000000
EXCHANGE (LOWER)	0.000000	0.000000	0.000000
WELLS	0.000000	0.000000	0.000000
DRAINS	0.000000	0.000000	0.000000
RECHARGE	23.590440	0.000000	23.590440
ET	0.000000	0.000000	0.000000
RIVER LEAKAGE	0.000000	0.000000	0.000000
HEAD DEP BOUNDS	1966.142500	16.490697	1949.651800
STREAM LEAKAGE	0.000000	0.000000	0.000000
INTERBED STORAGE	0.000000	0.000000	0.000000
RESERV. LEAKAGE	0.000000	0.000000	0.000000
SUM OF THE REGION	2362.955000	2362.823600	0.131411
DISCREPANCY [%]	0.01		

Table 7-5: Water budget of sub-region 5

FLOW TERM	IN (m^3/day)	OUT (m^3/day)	IN-OUT (m^3/day)
STORAGE	0.000000	0.000000	0.000000
CONSTANT HEAD	0.000000	0.000000	0.000000
HORIZ. EXCHANGE	1524.334900	5193.252100	-3668.917300
EXCHANGE (UPPER)	0.000000	0.000000	0.000000
EXCHANGE (LOWER)	0.000000	0.000000	0.000000
WELLS	0.000000	0.000000	0.000000
DRAINS	0.000000	0.000000	0.000000
RECHARGE	26.623080	0.000000	26.623080
ET	0.000000	0.000000	0.000000
RIVER LEAKAGE	0.000000	0.000000	0.000000
HEAD DEP BOUNDS	3778.854100	136.435350	3642.418800
STREAM LEAKAGE	0.000000	0.000000	0.000000
INTERBED STORAGE	0.000000	0.000000	0.000000
RESERV. LEAKAGE	0.000000	0.000000	0.000000
SUM OF THE REGION	5329.812100	5329.687500	0.124598
DISCREPANCY [%]	0		

Table 7-6: Water budget of sub-region 6

FLOW TERM	IN (m^3/day)	OUT (m^3/day)	IN-OUT (m^3/day)
STORAGE	0.000000	0.000000	0.000000
CONSTANT HEAD	0.000000	0.000000	0.000000
HORIZ. EXCHANGE	3842.202600	1614.450700	2227.751900
EXCHANGE (UPPER)	0.000000	0.000000	0.000000
EXCHANGE (LOWER)	0.000000	0.000000	0.000000
WELLS	0.000000	0.000000	0.000000
DRAINS	0.000000	0.000000	0.000000
RECHARGE	20.907720	0.000000	20.907720
ET	0.000000	0.000000	0.000000
RIVER LEAKAGE	0.000000	0.000000	0.000000
HEAD DEP BOUNDS	318.162580	2566.809000	-2248.646400
STREAM LEAKAGE	0.000000	0.000000	0.000000
INTERBED STORAGE	0.000000	0.000000	0.000000
RESERV. LEAKAGE	0.000000	0.000000	0.000000
SUM OF THE REGION	4181.272900	4181.259600	0.013254
DISCREPANCY [%]	0		

Table 7-7: Water budget of sub-region 7

FLOW TERM	IN (m^3/day)	OUT (m^3/day)	IN-OUT (m^3/day)
STORAGE	0.000000	0.000000	0.000000
CONSTANT HEAD	0.000000	0.000000	0.000000
HORIZ. EXCHANGE	2760.904700	612.291540	2148.613100
EXCHANGE (UPPER)	0.000000	0.000000	0.000000
EXCHANGE (LOWER)	0.000000	0.000000	0.000000
WELLS	0.000000	0.000000	0.000000
DRAINS	0.000000	0.000000	0.000000
RECHARGE	20.003760	0.000000	20.003760
ET	0.000000	0.000000	0.000000
RIVER LEAKAGE	0.000000	0.000000	0.000000
HEAD DEP BOUNDS	16.333112	2184.922900	-2168.589700
STREAM LEAKAGE	0.000000	0.000000	0.000000
INTERBED STORAGE	0.000000	0.000000	0.000000
RESERV. LEAKAGE	0.000000	0.000000	0.000000
SUM OF THE REGION	2797.241500	2797.214400	0.027146
DISCREPANCY [%]	0		

Table 7-8: Water budget of sub-region 8

FLOW TERM	IN (m^3/day)	OUT (m^3/day)	IN-OUT (m^3/day)
STORAGE	0.000000	0.000000	0.000000
CONSTANT HEAD	0.000000	0.000000	0.000000
HORIZ. EXCHANGE	2200.898500	433.083150	1767.815300
EXCHANGE (UPPER)	0.000000	0.000000	0.000000
EXCHANGE (LOWER)	0.000000	0.000000	0.000000
WELLS	0.000000	0.000000	0.000000
DRAINS	0.000000	0.000000	0.000000
RECHARGE	23.707080	0.000000	23.707080
ET	0.000000	0.000000	0.000000
RIVER LEAKAGE	0.000000	0.000000	0.000000
HEAD DEP BOUNDS	65.774957	1857.259400	-1791.484500
STREAM LEAKAGE	0.000000	0.000000	0.000000
INTERBED STORAGE	0.000000	0.000000	0.000000
RESERV. LEAKAGE	0.000000	0.000000	0.000000
SUM OF THE REGION	2290.380500	2290.342600	0.037931
DISCREPANCY [%]	0		

Table 7-9: Water budget of sub-region 9

FLOW TERM	IN (m^3/day)	OUT (m^3/day)	IN-OUT (m^3/day)
STORAGE	0.000000	0.000000	0.000000
CONSTANT HEAD	0.000000	0.000000	0.000000
HORIZ. EXCHANGE	1421.115400	85.227957	1335.887500
EXCHANGE (UPPER)	0.000000	0.000000	0.000000
EXCHANGE (LOWER)	0.000000	0.000000	0.000000
WELLS	0.000000	0.000000	0.000000
DRAINS	0.000000	0.000000	0.000000
RECHARGE	23.211360	0.000000	23.211360
ET	0.000000	0.000000	0.000000
RIVER LEAKAGE	0.000000	0.000000	0.000000
HEAD DEP BOUNDS	44.525426	1403.585800	-1359.060400
STREAM LEAKAGE	0.000000	0.000000	0.000000
INTERBED STORAGE	0.000000	0.000000	0.000000
RESERV. LEAKAGE	0.000000	0.000000	0.000000
SUM OF THE REGION	1488.852200	1488.813800	0.038475
DISCREPANCY [%]	0		

Table 7-10: Water budget of sub-region 10

FLOW TERM	IN (m^3/day)	OUT (m^3/day)	IN-OUT (m^3/day)
STORAGE	0.000000	0.000000	0.000000
CONSTANT HEAD	0.000000	0.000000	0.000000
HORIZ. EXCHANGE	918.498920	1569.458300	-650.959370
EXCHANGE (UPPER)	0.000000	0.000000	0.000000
EXCHANGE (LOWER)	0.000000	0.000000	0.000000
WELLS	0.000000	0.000000	0.000000
DRAINS	0.000000	0.000000	0.000000
RECHARGE	63.160561	0.000000	63.160561
ET	0.000000	0.000000	0.000000
RIVER LEAKAGE	0.000000	0.000000	0.000000
HEAD DEP BOUNDS	587.802070	0.000000	587.802070
STREAM LEAKAGE	0.000000	0.000000	0.000000
INTERBED STORAGE	0.000000	0.000000	0.000000
RESERV. LEAKAGE	0.000000	0.000000	0.000000
SUM OF THE REGION	1569.461600	1569.458300	0.003266
DISCREPANCY [%]	0		

Table 7-1: Water budget of overall model

FLOW TERM	IN (m^3/day)	OUT (m^3/day)	IN-OUT (m^3/day)
STORAGE	0.000000	0.000000	0.000000
CONSTANT HEAD	117.698840	154.190810	-36.491962
WELLS	969.408020	2756.159900	-1786.752000
DRAINS	0.000000	0.000000	0.000000
RECHARGE	2503.765100	0.000000	2503.765100
ET	0.000000	0.000000	0.000000
RIVER LEAKAGE	0.000000	0.000000	0.000000
HEAD DEP BOUNDS	7604.115500	8284.234800	-680.119320
STREAM LEAKAGE	0.000000	0.000000	0.000000
INTERBED STORAGE	0.000000	0.000000	0.000000
RESERV. LEAKAGE	0.000000	0.000000	0.000000
SUM	11194.987000	11194.586000	0.401367
DISCREPANCY [%]	0		