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**Assessment of Groundwater Flow Using MODFLOW in
As Suwayq, Oman**

Raya Hilal Mohammed Al-lamki

A thesis submitted in partial fulfillment
of the requirements for the degree

Master of Science

in

Civil Engineering (Environmental Engineering)

Department of Civil and Architectural Engineering

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Assessment of Groundwater Flow Using MODFLOW Model in As Suwayq, Oman

Abstract

As Suwayq represents one of the crucial fertilized area along Al Batinah coastal plain in north of Oman. Groundwater mainly used to supply agricultural, animals production, domestic and industrial activities. In 1970's, the development in different lives sectors such as electricity led to serve exploitation which in turn affected the quality of the used water. By this salinity became the main concern since 1980's that have to be given a priority to be mitigated. This was established through continuous research studies to monitor the happened deficit to come with sustainable management plans. As a result, capturing this phenomena through modeling to simulate the situation of groundwater numerically in reference to abstraction and recharge rates remains the main aim for this study to be highlighted. Similarly, suggesting new plans to tackle the continuous decline in water head still represents one objective belonged this research.

In this study, MODFLOW was implemented as three dimensional code to visualize the actual system of groundwater through 2010 up to 2017. Uncertainty in MMRWR data and unavailability of some of them imposed the model to be calibrated. The calibration basically was sensitive to interflow recharge from Jabel, abstraction and hydraulic conductivity. Through calibration, good agreement between computed and observed heads was achieved ($R^2=0.993$) in

steady state simulation. Addition to this, strong relation was obtained the in transient computation with a correlation coefficient R^2 of 0.977. Likewise, the simulated well hydrographs show closed behavior to observed ones as illustrated in transient flow simulation.

The model showed the existence of reverse seawater intrusion as a moment that extraction from storage overcomes the recharge. The drop in head had exceeded four meters beneath sea level exclusively in coastal wells. This growing phenomena shall be reclaimed through dense effort by making new decisions to recover the falling in head. The optimal management system can be achieved either by minimizing the daily extraction or by applying artificial recharge from tertiary treated wastewater (TWW) or desalinated water. Using managed aquifer recharge (MAR) in term of artificial recharge is able to save up to 335 MCM from deterioration as impacted by intruding seawater by end 2035. Beside to the ability of artificial recharge to deviate seawater, it is able to increase the storage and achieve the desired groundwater sustainability.

تقييم تدفق المياه الجوفية في ولاية السويق باستخدام نموذج MODFLOW

ملخص

تمثل ولاية السويق إحدى البقع الخضراء الخصبة على امتداد شريط الباطنة الساحلي. المياه الجوفية تستخدم فيها بشكل أساسي لتلبية الأغراض الزراعية و الانتاج الحيواني بالإضافة إلى الأنشطة الصناعية. أدى التطور الذي عم مختلف نواحي الحياة منذ 1970 بما فيها قطاع الكهرباء إلى استنزاف كميات طائلة من المياه مما أثر سلباً على جودة المياه المتاحة. كل ذلك جعل مشكلة الملوحة أهم المشكلات التي يتناول دراستها لتفادي العجز المائي الحاصل في المنطقة من خلال عمل نماذج لتقييم الأوضاع المائية.

في هذه الدراسة تم استخدام نموذج MODFLOW ثلاثي الأبعاد لعمل نموذج متكامل للمياه الجوفية في المنطقة في الفترة من 2010 إلى 2017. عدم دقة البيانات المتوفرة من وزارة البلديات الإقليمية و موارد المياه أدى إلى معايرة بعض عناصر الهيدرولوجيا والتي لها دور مباشر في التوازن المائي مثل التغذية من الجبال و السحب من المخزون الجوفي. بعد المعايرة وجد توافق في العلاقة بين مستويات المياه المحسوبة و قياسات مستويات المياه في آبار المراقبة.

أشارت نتائج النمذجة إلى وجود تداخل عكسي لمياه البحر باتجاه الداخل حيث أن الضخ يفوق التغذية الحاصلة. ففي الآبار الموجودة على الشريط الساحلي وجد أن الانخفاض في المستوى المائي يتجاوز أربعة أمتار تحت مستوى سطح البحر. لذلك لابد من تكاتف الجهود لتقليل ظاهرة الملوحة و التناقص المستمر في مستويات المياه. كل ذلك يمكن أن يتم الحصول عليه إما عن طريق وضع قواعد و سياسات لتقليل الاستنزاف المستمر و إما عن طريق حقن المياه المعالجة ثلاثياً إلى الحوض الجوفي.

الخيار الأخير يضمن حفظ 335 مليون متر مكعب سنويا من التلوث الحاصل نتيجة تداخل مياه البحر ليس ذلك فحسب بل أنه يضمن ارتفاع المستوى المائي مع نهاية 2035.

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Chapter 1

1. Introduction

1.1 Background

Sultanate of Oman locates in the arid zone in the southeast of the Arabian Peninsula. It has an annual average rainfall of less than 100 mm (Abdel-Rahman and Abdel-Magid, 1993). In Oman, the usage of groundwater in agriculture forms about 93% through which over 53% of the cultivation activities are suspended in Al Batinah region (Zekri, 2008). An intense use of groundwater practically occurs in dense populated areas and through which farming practices demand more than 80% of groundwater resources. All of these led to long term depletion of groundwater storage and hence reverse seawater intrusion (Al Barwani and Helmi, 2006; MRMEWR, 2005).

The growth in the agricultural exercises in Al Batinah which is purely associated with massive exploitation from the groundwater storage led to salinity. Rajmohan et al. (2009) recognized that the approximate annual drawdown to be 0.3 – 0.4 m and this rate is declined more and more since there is continues abstraction. Furthermore, traditional agriculture methods through over pumping accelerate seawater intrusion and in turn salinity of soil. All of these produced large disturb in total lands used for agriculture so that more than 44% of productive lands suffer from salinity (Ahmed et al., 2013). Therefore, alternative water resources are needed to augment stressed coastal aquifers.

To capture the phenomena of groundwater situation in contaminated area along the north coastal plain of AL Batinah and issuing management plan to reclaim seawater intrusion. Several studies were installed to detect the phenomena of groundwater flow and its relevant seawater intrusion through usage of modeling techniques in Batinah north such as Sana and Al-Shibli (2003), Chitrakar and Sana (2015) and Al-Maktoumi et al. (2015). The same objective was carried in the southern part of Oman, Salalah by Shamma and Thunvik (2009). Beside to this, various global researches were constructed to sustain groundwater problems (Fowler et al., 2015; Ghoraba et al., 2013; Jang et al., 2016). All of them gave comprehensive overview to simulate the concerned area based on available hydrological data in response to recharge and extracted water from the aquifer.

Three dimensional MODFLOW model is an important modeling tool to simulate the sustainability of groundwater in As Suwayq through converting complicated hydrological conceptual model to three dimensional (3D) finite differential grids. This cells or mesh grid system is capable enough for decision makers to formulate new strategies to eliminate the decline in water table. Also, it allows to find another alternatives to mitigate the risk of contaminant and provide future remediation by seeing the feasibility of managed aquifer recharge (MAR) by injecting tertiary treated wastewater (TWW) or desalinated water from operated plants.

1.2 Problem Statement

Greatly demand of groundwater in arid climate is sufficiently enough to create vast hazard for water and agricultural activates in Al Batinah region. Many farms were migrated and lost their unique value since Al Batinah coastal plain acts as the central backbone for the agricultural activities in Oman.

In 1970's, after the development in all sides of lives in Oman that led to operating of electricity plants everywhere, people started to use modern pumping motors instead of traditional methods in withdrawal of groundwater. This initiated the concept of seawater intrusion and thus the salinity of soil. The soil became unsuitable to grow many crops that were adopted to be grown in that agricultural area. The cultivated crops especially vegetables and fruit did not meet food security demand so, the government had initiated the policy of import from other countries. The economic value of the area has been impacted since each year an average of 18.9 to 36 million USA\$ represent the generated loss in response to salinity (Hussain, 2005). The seawater intrusion struggle and thus salinity concern did not affect the coastal areas only but its configuration reached to interior places of Al Batinah.

Al-Barwani and Helmi (2006) reported in study of salinity from As'Seeb to As Suwayq that the advancement of seawater intrusion extended to approximately 12 km inland at Barka. Similarly, between 2000 and 2005, around 21.14 km of agricultural lands were destroyed and lost their fertilities because of high level of salinity (2- 6 $\mu\text{S}/\text{cm}$) by end of 2005. The water resources deficit according to statistic of (MWR, 2000) grew to more than 90 MCM.

1.3 Objectives of the Study

- To achieve better understanding of the sophisticated hydrological system in the study area in term of geology, sources and sinks and boundary conditions. All of these will help to construct integrated conceptual model.
- To employ the concept of groundwater balance to determine all sources of water come into and out of the aquifer system. This is a tool to see the situation of groundwater in concerned area.
- To analyse available data from MRMWR and notice their fluctuations in the whole duration with a trial to correlate them to build general understanding for the area.
- To practice finite three-Dimensional numerical model (MODFLOW) as a management tools to evaluate the mechanisms of groundwater flow in AL Suwayq, one wilyat of Al Batinah.
- To estimate net groundwater budget in term of recharge and extraction using calibrated system to evaluate the recent and future conditions of water balance.
- To utilize the developed calibrated model to see the response of aquifer under different management scenarios. These judgments can show representative picture for the aquifer condition in the future coming years.

1.4 Thesis Outline

The achievement of the objectives of this study are answered in the chapters of this thesis. Global and local studies belong groundwater modeling are presented in chapter two to give an idea about the modeling experience in and out Oman. Chapter 3 describes the study area and relevant available data as geology and hydrology. Chapter 4 reveals the construction of the conceptual model with sorting of all data that need to be included in conceptualization process. The results of the modeling process involving calibration, sensitivity analysis, validation and predictive scenarios are visualized in chapter 5. Finally, Chapter 6 gives overall conclusion with suggested recommendations.

Chapter 2

2. Literature Review

2.1 Groundwater Modeling

The pervious few years showed a huge revolution to view the flow mechanism and thus contaminant transport using computational models (Todd and Mays, 2005). Essentially, groundwater models rely on conservation of mass and Darcy empirical formula to represent the 3D flow (Harbaugh et al., 2000; Harbaugh and McDonald, 1996). The estimation of the model equation is done through finite grid or finite difference computations or combined together.

The success forecast of the model is based on parameters of simulation and the reasonable margin conditions. Regarding the boundary conditions, it is eventually necessary to make sure that mesh nodes overlap with aquifer features or observation wells (Todd and Mays, 2005). The numerical groundwater model is functioned to monitor the impact of discharge in zone of interface between freshwater and saline water in the coastal plains (Zekri et al., 2015).

Management of water resources is established through computational models to reflect the dynamic properties of aquifers. MODFLOW is one common software to simulate confined and unconfined aquifer (Zekri et al., 2015). MODFLOW-2000 is a computer software that represent either one, two or three- dimensional groundwater flowing system by means of finite difference discretization (Harbaugh and McDonald, 1996).

MOFFLOW-2000 is able to view steady and transient flow in a system of many layers having non-uniform shapes. The geological strata system can be confined, unconfined or contains both stratus. It can simulate different scenarios such as recharge, flow through river beds, flow to drains and evapotranspiration (Todd and Mays, 2005). MODFIOW is able to detect the head distribution in porous media through finite digitized cell representing the aquifer. Several scenarios including discharge and recharge can be inserted to see the impact of them in

hydraulic head and in turn the opportunities of seawater intrusion (Harbaugh and McDonald, 1996).

In the simulation process, both steady and transient states have to be modeled. The steady state simulation seeks to view the mechanism of groundwater flow and establish primary state to be basic for the calibration process. In this manner, the calculated steady state heads are inserted as the primary heads for the transient system (Shammas and Thunvik, 2009).

According to (McDonald and Harbaugh, 1988; Todd and Mays, 2005), the simulation of aquifer based on MODFLOW implies the existence of saturated flow condition, the validity of Darcy's formula, the achievement of isotropic condition through which no variation in directional properties of hydraulic conductivity and transmissivity of the aquifer and density of groundwater has to not change with time. MODFLOW model is able to clarify all the features in the aquifer such as wells, streams, recharge either from agricultural lands or directly from rainfall, and evapotranspiration.

Groundwater modeling is vital process that undergoes several steps. It is a complementary process that needs to follow different stages in order as follows:

- **Defining purposes:** It is the first step in any model system. By clarifying all objectives, accuracy of the model can be easily determined and it saves effort and time.
- **Selecting computer code:** It essential to decide the suitable computer code that converts the groundwater flow and suspended solute transport mathematical expressions to numerical solutions. The selected software basically based on the complexity of the conceptual model and identified objectives. In any computer's code, many considerations have to be sorted as (1) model type, 2) time dependency: steady or transient model; (3) dimensionality; (4) ability to describe the aquifer properties: homogeneous or heterogeneous; isotropic or anisotropic media; (5) ability to include various hydrological stresses; (6) user friendliness; and (7) requirements on the computer facility and time interval.

- **Designing numerical model:** The design of numerical model involves the design of model grids, selection of stress periods and time steps deciding boundary conditions. The conceptual model will be elementary base for numerical grid model.
- **Determination of model inputs:** The inputs to the model requires data in term of initial and boundary conditions, hydrogeological parameters, and hydrological stresses. The data for all these inputs have to be include all grid points for all stress periods.
- **Calibration of the model:** The calibration process implies the output heads to be approximately closed to the field measured records through the adjustment of aquifer parameters or stresses. This can be either by trial and error or automated parameter estimation method. Then, sensitivity analysis is conducted to calibrated system to examine the predominant of model uncertainty and boundary conditions on resultant of the system.
- **Validation of the model:** To see to what extent the model is valid to have future prediction. The calibrated model is functioned to implement new set of available data using new duration of time.
- **Application of the model:** The calibrated model is applied to predict the response of the aquifer system under future events. Similarly, the calibrated model is used to run predictive scenarios with future hydrological stresses.
- **Presentation of results:** The modeling procedure is showed clearly through qualified presentation for modeling processing and results.

2.2 Groundwater Flow Theory

Darcy's law predicts the flow flux v in conductive strata with respect to the hydraulic gradient which decreases as the progress of flow takes place as a result of friction. It evaluates the constant discharge in steady flow through which the mass or energy is conserved.

The unsteady 3-D partial differential equation in anisotropic and heterogeneous confined aquifer is given below as

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) \pm W = S_s \frac{\partial h}{\partial t} \dots\dots \text{Eqn(1)}$$

Where K_{xx} , K_{yy} and K_{zz} are the hydraulic conductivities in x, y and z direction respectively (L/T); h is the piezometric head (L) and W is the volumetric flux per unit volume and represents the sources and/or sinks of water per unit time (T^{-1}) S_s is the specific storage of the strata (L^{-1}); and t is the time duration (T). W is a function of both space and time (x,y,z,t). Conversely, K_{xx} , K_{yy} , K_{zz} and S_s are functions of space only (x,y,z).

The properties of any geological aquifer are referred to calculation of both hydraulic conductivity and specific storage and in turn storage coefficient. The steady state when the right hand side of above equation is zero is established to estimate the hydraulic conductivity. The constant or steady state will remain basically as a base for the transient state that governs to estimate the specific storage of the strata.

The equation is solved by numerical model such as finite differences to represent the geological strata. Through it a network of finite elements in space and time is built and inserting the initial head and the boundary limits to simulate the system properly. As a result, a couple of computational linear algebraic equation are generated from this technique. They can be iterated by changing the heads at certain points and times which reflects the period of the decline in head. (Figure 2-1) explains three-dimensional aquifer system digitized into finite grids. It has three components; rows, columns and layers. Layers commonly represent intervals or geohydrological units such that k index reveals the variation in reference to z- vertical direction. Furthermore, rows and columns are parallel to x and y- direction respectively.

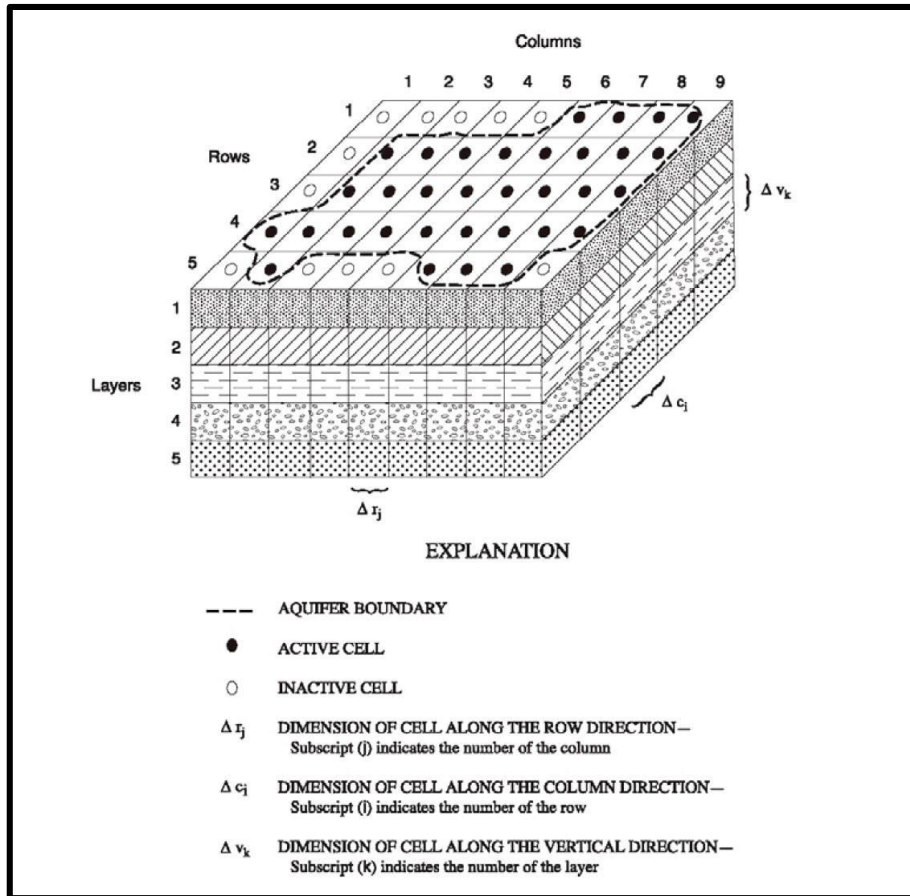


Figure 2-1: Grid or finite difference system in MODFLOW (McDonald and Harbaugh, 1988)

2.3 International Studies

us Saba et al. (2016) had applied one study to simulate hydrological groundwater system in Moradabad city lying between rivers Ramganga and Gagan, India. It had an objective to visualize the socioeconomic resulted from extraction of groundwater lies in an average of hydraulic conductivity between 720 and 864 m/day. Percolated rainfall water presents the main source of recharge. The higher concentration of chloride resulted from abandoned military bones in the northern area and landfill disposal in southern part. It reached to 26-537mg/l in pre-monsoon, 2012 and 23-511mg/l in post monsoon, 2013.

Jang et al. (2016) found that seawater intrusion and land subsidence are mainly wide problems in Pingtung Plain area of Taiwan produces by serve abstraction

from the aquifer. This study was looking for the valid lands for surface water utilization to lower the extraction activities in this area. MODFLOW was conducted to compute the rise or recovery of water table after replacement of pumped groundwater with surface one. This also led to better improvement in water quality for further usage for drinking, aquaculture and irrigation.

Ghoraba et al. (2013) had conducted one research in The Nile Delta especially central part in El- Gharbiya Government, is one of highly agricultural dense area in Egypt. It suffers from shortage of healthy sewer system and this in turn resulted in groundwater contamination. This had affected the cultivated soil. Remediation of contaminant of water and thus soil was simulated through using MODFLOW and MT3DMS. This was suggested through construction of abstraction wells to withdraw the contaminated water by ammonium in Birma region where the concentration is too much.

Fowler et al. (2015) detected in their research that type of crop sometimes forms huge concern toward water resources availability especially if it consumes large amounts of abstracted water. MODFLOW-FMP2 were basic modeling objects to simulate the selection of planted crop versus the amount of discharging water. Similarly, it can reveals the most efficient irrigation system to give better yield with low water consumption. DAKOTA is used to present the simulated MODFLOW-FMP2 results in easily designed classes.

Zhang et al. (2013) had obtained that the type of land use impacts both of quantity and quality of groundwater. Dense agricultural usage of lands led to an increase in nitrate concentration in Sherwood Sandstone aquifer in Britain. This study was installed to magnify the loss of nitrate into the aquifer and forecast its amount in the future utilizing MODFLOW and MT3DMS as representative numerical instruments. Applying some radical or root alterations in land use however kept the concentration of nitrate to be as 50 mg/l by end of 2025. This means that additional decades will be required in an attempt for completed remediation or mitigation of highly concentrated nitrate.

2.4 Local Studies in Oman

Kalbus et al. (2016) Installed one study in As Suwayq area to simulate the groundwater flow and related quality using numerical code of SEAWAT in the duration of 1974-2010. The calibration of the model was basically relied on inflow from the mountains and abstraction rate to be as 71 and 164 MCM/year by end of 2010. This implies that the struggle of seawater intrusion happened in earlier time after 1970s (Figure 2-2). This coincide with (OSS, 2012) approach that 2% of agricultural areas in Batinah–north has very high saline water. They did three future management scenarios to detect their response on groundwater and they are: encouraging farmers to replace traditional irrigation systems with smart automated ones, strategy of dams' construction and applying both at the same time. Recharge dams acts as the best management tool to provide 68% of freshwater by end of 2040.

Amerjeed (2016) did a complementary study in Al Farah catchment (nearby to study area from the east boundary) through functioning of MODFLOW as a basic modeling tool in 1993-2013. Recharge was estimated through applying both of water-table fluctuation (WTF) and chloride mass-balance (CMB) methods to give better understanding about recharge estimation in any hydrological system. Then, these two combined methods were compared with obtained recharge from MODFLOW since they have some drawback issues. The study had emphasized the presence of long term seawater intrusion hazard during 1980s and this interface still advance more due to huge daily demand of limited groundwater resources.

Chitrakar and Sana (2015) had established one paper to reflect the groundwater situation in Barka which have challenges regarding groundwater resources in the period of 1985 to 2010. They utilized MODFLOW and MT3DMS to capture the phenomena clearly. Abstraction was estimated to be five times higher than recharge and this led to a decline in water head to 7 m by end of 2010. Saving water resources through further artificial recharge either by TWW or desalinated

plant with an amount of 150,000 m³/day is sufficiently enough to stop seawater intrusion and rising water table for the next 14 years.

Sana and Al-Shibli (2003) did an integrated research to evaluate water balance in terms of discharge and recharge using MODFLOW and MT3DMS in Wadi AL Jizi area, Sohar. The transient model was built through 1988 to 2001. This calibrated model is enough for further management systems by decision makers. The calibrated model essentially depend in actual abstraction rate that leads to accurate situation easily.

Abdalla and Al-Rawahi (2013) had utilized MODFLOW and MT3DMS to investigate the groundwater flow and related quality in quaternary alluvium with three sub-units aquifer in AL Khoud catchment area. Direct percolation from rainfall, wadi flow, interflow from south boundary and dams are the main components of recharge process. Dam contributes with a rate of 24-30% in recharging the aquifer followed by 24 and 12% from wadi discharge and infiltration from precipitation. Nevertheless, increased extraction from the storage led to seawater intrusion phenomena.

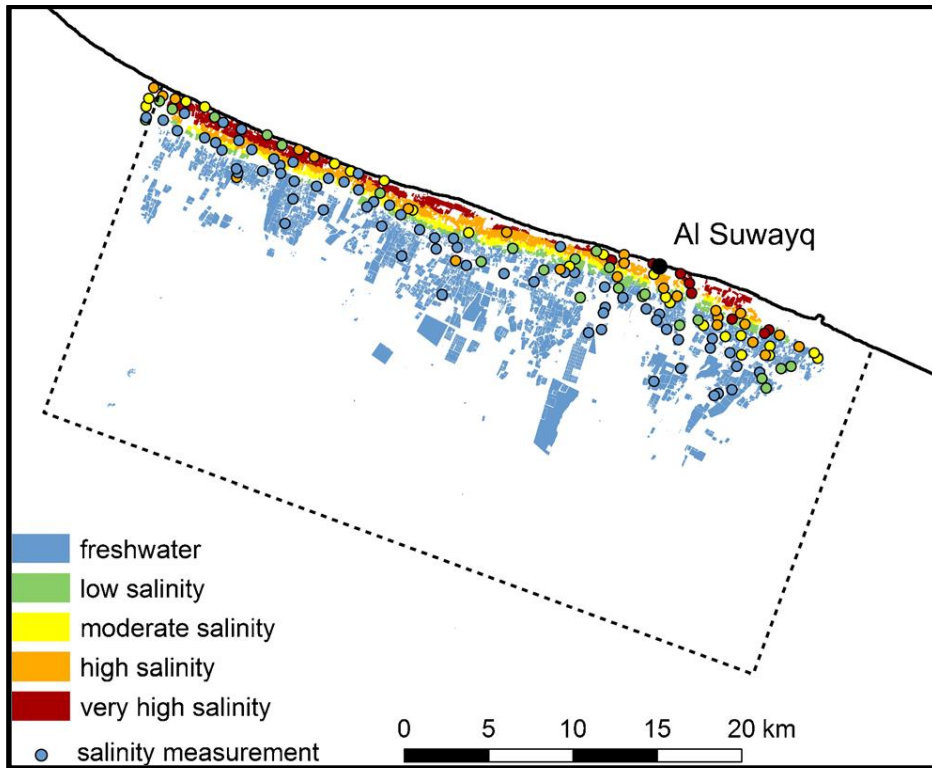


Figure 2-2: Salinity Measurements in As Suwayq Area (Kalbus et al., 2016)

Izady et al. (2017) similarly used MOFLOW in transboundary hardrock alluvium aquifer in AL-Buraimi. The objective of the study was to monitor the groundwater in an aquifer consisting of four hydrological units (Hawasina, Ophoolite, Tertiary and Alluvium). It can assist to produce integrated water balance estimation for future modeling studies across UAE boundary. An average of 5.67MCM/year represents the calibrated lateral groundwater inflow from fractured mountains in a duration of 17 years (1996-2013). Also, in the same area, (Jang et al., 2016) studied groundwater recharge in term of percentage of effective hardrock thickness in the same area through which effective recharge was managed by combined water-table fluctuation and groundwater balance methods. Extraction from storage varies in response to standardized precipitation index (SPI). In drought period, it reaches about 36 Mm³/year as maximum withdrawal rate comparing to 14.5 and 16.3 Mm³/year in wet and usual climate conditions respectively.

(Grundmann et al., 2012) had evaluated the long term interaction of hydrological, metrological and cultivation activities on optimization of sustainable groundwater management system in Batinah north using APPM (Assessment, Prognoses, Planning and Management) as modeling tool. It showed the impact of each interaction with respect to salinity, crop yield and obtained profit. It illustrated strong correlation among lands productivity and management of groundwater through quantity and quality.

Al-Maktoumi et al. (2015) had implemented MODFLOW-2005 and MT3DMS to detect the feasibility of MAR (Managed Aquifer Recharge) through injection of tertiary treated wastewater (TWW) to mitigate deteriorated coastal Jamma aquifer. Four months is required for injection process of 60,000 m³/day followed by another eight months for recovery. The injection was more efficient in mountain upstream areas in contrast to downstream however it implies much time. It assists to minimize migration of injected TWW to the sea and it contributes to improve water quality of the aquifer.

Zekri et al. (2015) addition to MOFLOW, two numerical codes were conducted to simulate uncertainty occurred in both of recharge and extraction from Al-Khoud aquifer in Muscat. MCS (Monte-Carlo Simulation) was used to find out the resulted uncertainty in recharge. On the other hand, MODFLOW was used to monitor the changes in groundwater based on daily pumping. The second code was linked to NSGA-II (Non-dominated Sorting Genetic Algorithm-II) to predict optimal solutions according to future recharge scenarios. These scenarios were installed to evaluate their response in groundwater in wet and dry durations for 12 years.

Abdalla and Al-Rawahi (2013) had checked the role of dams in recharge process in AL Khoud area in Muscat using water table fluctuation method. In the wet rainfall durations of 1997, 2003 and 2005, percolated water through dams was estimated to be 15, 22 and 25 Mm³. Dam construction and opening of Barka desalination plant in 2004 reduced daily consumption by abstraction rate by 20-

foldsbe and thus had contributed to resolve drawdown in water head to be zero in downstream fans area.

Shammas and Thunvik (2009) had introduced integrated study to compute transient flow of groundwater in Salalah and its corresponding solute particles through MODFLOW and MT3DMS respectively from 1993 till 2005. Beside to flow from Jabel and direct recharge from rainfall, there are artificial recharge wells in coastal plain to enhance the process of recharge. It was found that about of 56 MCM represent the yearly total recharge divided to be 90% as inflow from Jabel, 9% from irrigation return and only 1% from rainfall. Conversely, these sources of recharge do not cover the demand of groundwater by abstraction since it is 16% more than input recharge and this rate will grow up to 21% by end of 2020.

Chapter 3

3. Study Area

3.1 General

As Suwayq Williate locates in north of Oman and it is a part of Al Batinah coastal plain. It is 135 km far from the capital Muscat along coast line. It forms the biggest area in Batinah north of 3840 km². It is bordered by Al Khabourah from the west, Al Musanaah from the east, Al Hoqain from the south and Gulf of Oman from the north. Wadi Bani Ghafir and Mayhah-Mabrah- Hajir system (Jahawir) represent the crucial catchments over the area of the study (Figure 3-1). All of these catchments bounded by Jable in the south and by Gulf of Oman in the north. Jahawir Hajir and Ghafir systems are considered as the biggest catchments in Al Batinah with an area of 1387 and 1252 km² respectively (OSS, 2012).

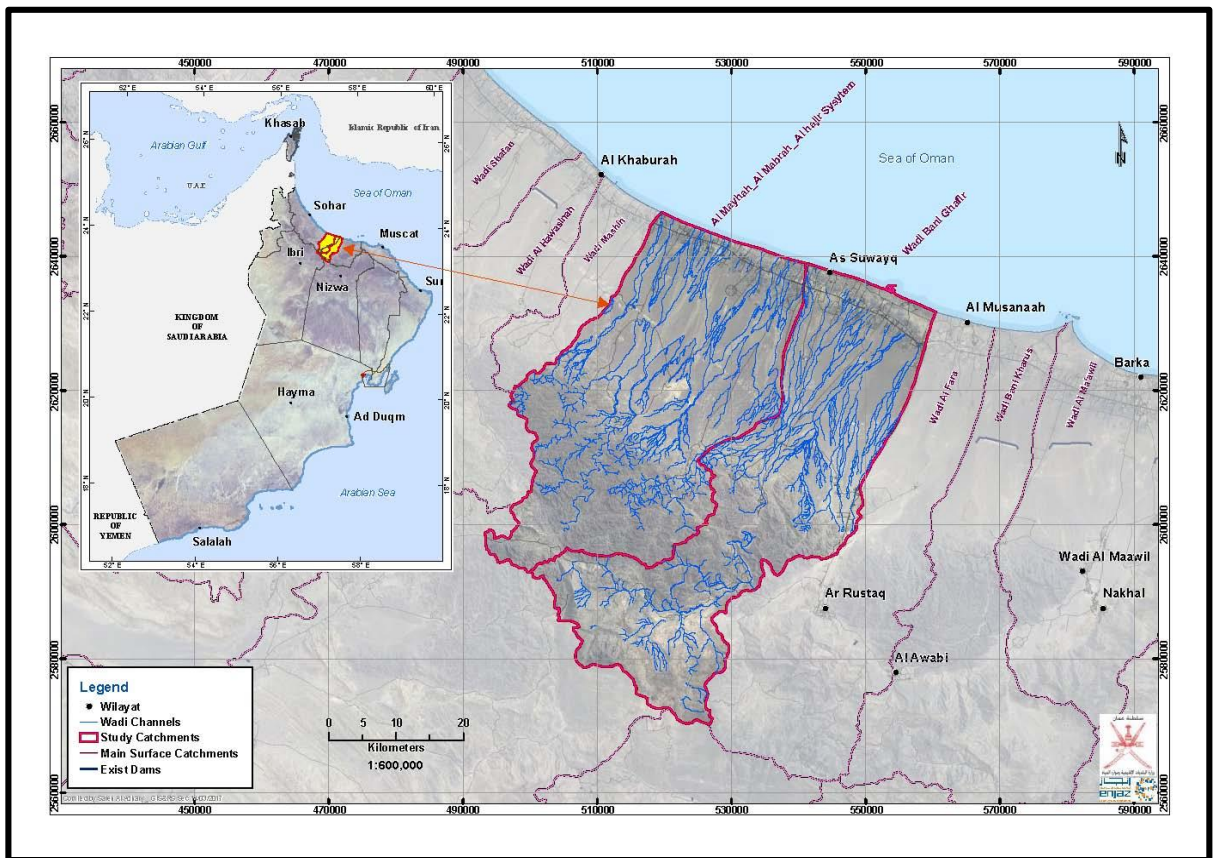


Figure 3-1: The Study Area

3.2 Topography

The topography of As Suwayq ranges from 2500 m in the south (Jable area) to coastal sea level in the north. This gives a steeper surface gradient in southern Jabel area and flatter or shallow surface in northern coastal plain. The steeper topography in the south extends up to 3000 m near the Jabe Al Akhdar. in the southern boundary of Al Batinah governorate (OSS, 2012) and (Amerjeed, 2016).

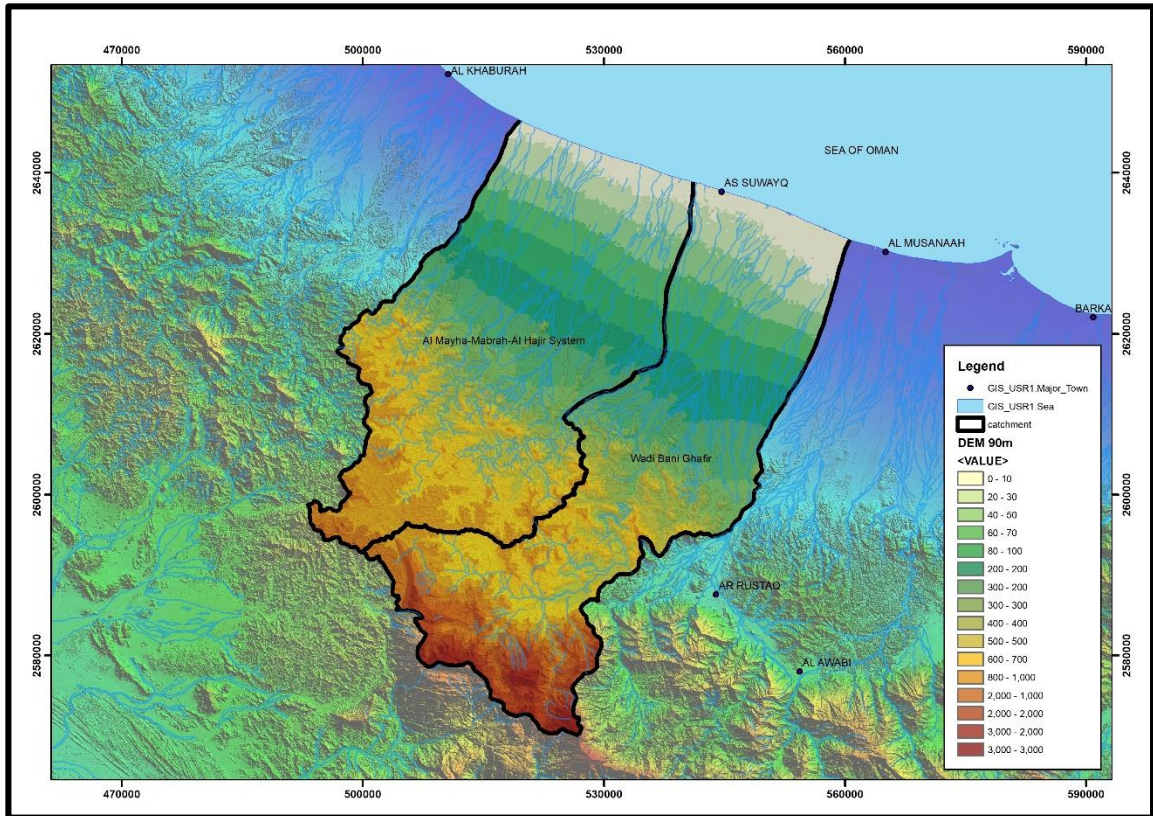


Figure 3-2: Topography of the Study Area

3.3 Climate

Both the mean and maximum annual temperature in Al Suwayq have increased with respect to climate changes and this increase in temperature is followed by an increase in humidity. In this manner, the maximum daily temperature can reach up to 48C⁰ during summer periods while the typical annual temperature lies in the range between 26 and 29 C⁰ (Khatri, 2011).

3.4 Land cover

As Suwayq is the biggest wilayat in Al Batinah area with an agricultural production of 20.5% (S. Choudri et al., 2013). It has dense vegetation since around 8000 farms are cultivated in this area. Vegetable crops form 51% of cultivated lands which form 104 km² of the total area. The rest 24% and 16% of these areas are grown with forage and date palm trees respectively (MAF, 2014).

Seawater intrusion is the main threat in this area due to huge daily pumping so many cultivated areas were deteriorated and the cropping yields decrease. The government has introduced one strategy to protect groundwater resources through limitation of their uses and achievement of sustainability (Zekri et al., 2015). According to statistics of MWR in 1996, over exploitation from the aquifer in nearby Al Khabourh area was 16.43 Mm³ and this rate is continuously growing as a consequence of dense agricultural practices (Abdalla et al., 2010). In addition to this, Wadi Al Mayha-Mabrah-Al Hajir suffers from an extensive yearly deficit in groundwater storage of 79Mm³ which was the highest in Batinah area (OSS, 2012).

3.5 Geology

According to boreholes project in North-Al Batinah, the geology of aquifer mainly consists of Neogen-aged Upper Fars overlies by Quaternary-aged Alluvium (MRMWR, 2006). These two geological formations form the main source of aquifer groundwater in wells (OSS, 2012).

It is obviously seen in Figure 3-3 that in the direction from north-east to south – west of Al Batinah the alluvium and upper fars are the most efficient aquifers where middle and lower fars have neglected amount of water and no water respectively. Hadhramaut is potentially poor aquifer. Overall, the thickness of all of these layers become narrow in the extent to the west and Hawasinah nappes aquitard appears at the end of the cross section with small thickness (MRMWR, 2006).

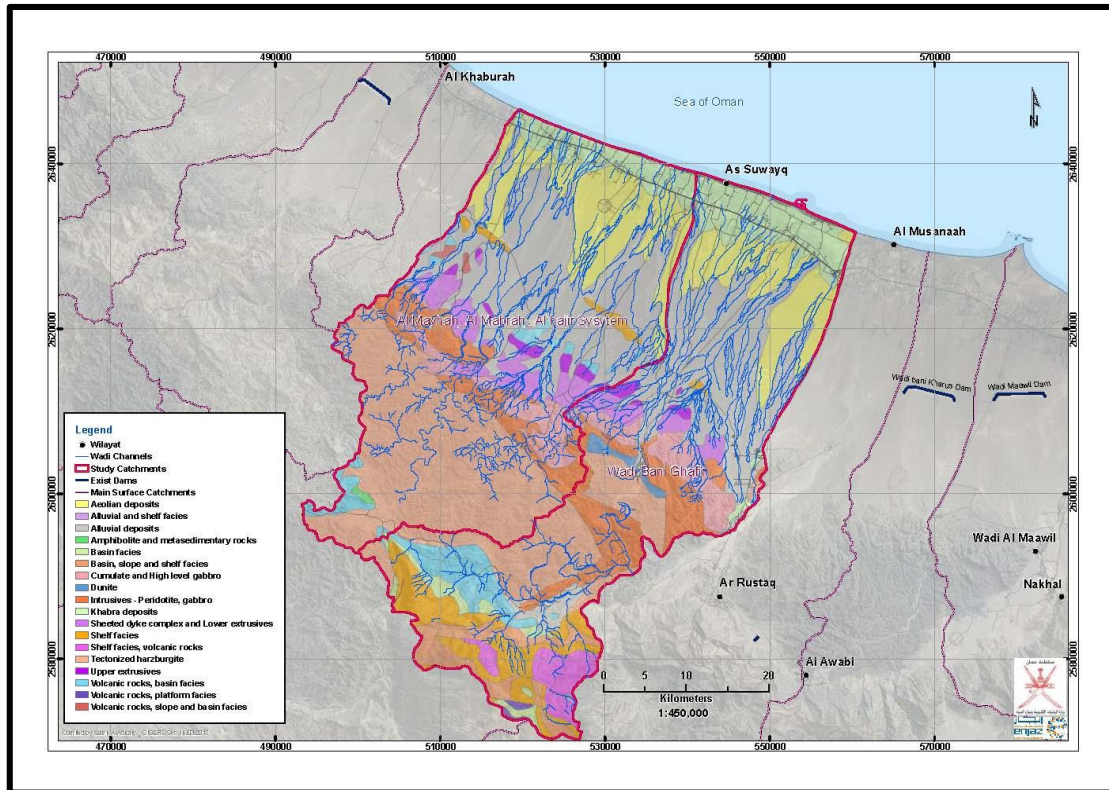


Figure 3-3: The Geology of the Study Area

3.5.1 Alluvium

Since As Suwayq is a part of north Batinah, it has a series of alluvial fans and fan remnants associated with quaternary recent alluvium of less cementation materials. It forms of unconfined aquifer under water table (OSS, 2012). The alluvium formation consists of loose weathered limestone and ophiolite gravels with interbedded clays (MRMWR, 2006). According to (MWR, 1995b), the thickness of alluvium fluctuates with a range of 52-312. Also, (Kalbus et al., 2016) had implemented one study in one village Suwayq and concluded that a layer of 16 -50 m of alluvium formation extends over 213-582 m of upper fars formation.

3.5.2 Fars Group

This group located under alluvium formation. The Fars formation in the concerned area does not contain noticeable outcrops compared to eastern part of south Batinah near Seeb. There are three classifications under this aquifer of Neogene's age upper fars, middle and lower (GRC, 2004, 2006; MWR, 1993a).

Upper Fars

Upper fars layer is composed of dolomites, cemented conglomerates, and chalky limestones (MRMWR, 2006). The upper fars or continental facies consists mainly of dolomites, dolomitic cemented conglomerate and chalky limestone. It is known as "upper conglomeritic Fars" because of existence of conglomerates. Upper fars in north Batinah represent a thickness of 114-582 m and large layer of upper fars formation is usually obtained in wadi Bani Ghafir (OSS, 2012).

Middle and Lower Fars

The middle Fars consists of green, purple and dark reddish brown mudstone/clayston. The top of the middle formation and bottom of upper fars are similar. Variably and thin cemented gravels are interbedded with these sediments. Alteration in reducing environment as noticed through the change in the color of the siltstones and mudstones reveals the presence of upper fars formation (Amerjeed, 2016). It is sometimes called "Fars evaporites" since it has ability to degrade into shale and might evaporate (MRMWR, 2006).

The intermediate fars semimprevios confining aquitard is formed by claystones. It is seems as aquitard and it generally impermeable aquifer. It is common between wadi Jizi and Al Farra (OSS, 2012) and it has small thickness in this study area. The marine or lower fars aquifer grey shale, brown and weak brown with interbedded silty limestone. The groundwater of middle and lower fars mostly contains sodium bicarbonate and magnesium bicarbonate (MRMWR, 2006).

3.6 Rainfall

Rainfall data is an important tool to represent the actual hydrological system in the study area (Amerjeed, 2016). Rainfall records were obtained from MRMWR in daily basis and they were measured in millimeters. There are ten different rainfall gauge stations in both catchments. According to MRMWR data, only two gauge stations have available data as noticed in Table 3-1.

Table 3-1: Mean Monthly and Annually Rainfall in Al Raq and As Suwayq Gauge Stations

Staion	Elev (m)	Average Monthly Rainfall (mm)												Average Annual Rainfall (mm)
		Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	
AL RAQ	120	5	7	11	6	3	14	8	2	3	7	11	7	82
AS SUWAYQ	26	7	6	9	7	2	10	12	5	1	12	15	7	92

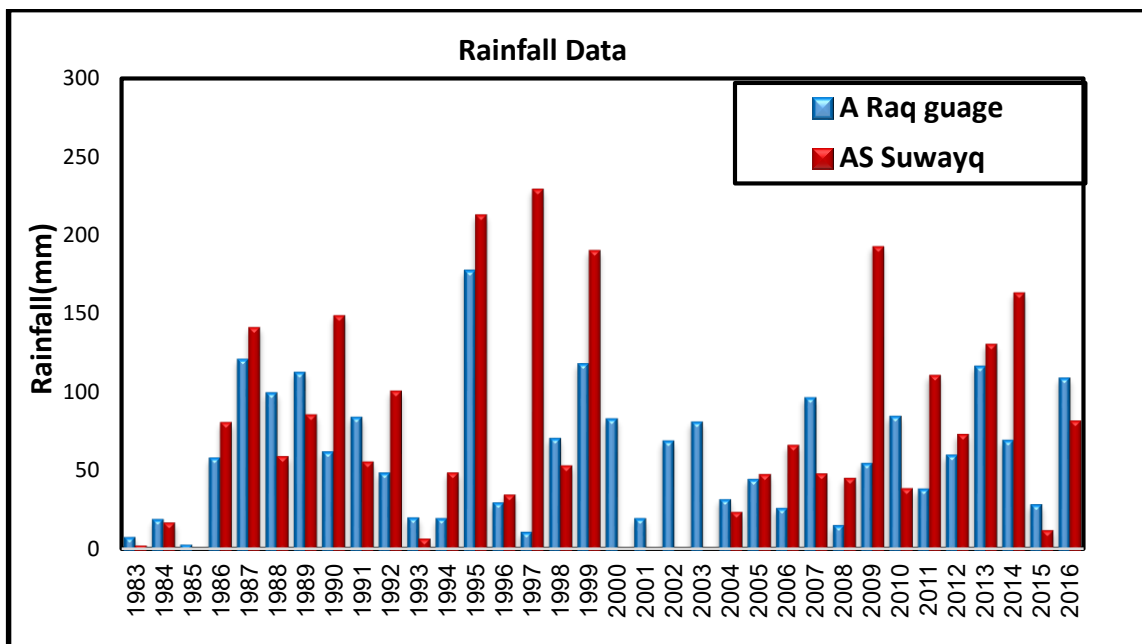


Figure 3-5: Annual Rainfall in Al Raq and As Suwayq Guage Stations

3.7 Wadi Flow

According to Figure 3-4, there are three wadi gauges in the study area. Only wadi stations in Ghafir catchment have sufficient available data compared to Mabrah catchment. There are two stations located in the valley zone with an elevation of 194 and 225 m at Falaj Al Saidi and Al Houqain correspondingly. Water stage recorder and crest stage gauge are utilized to measure the wadi flows through slope – area measurement (Amerjeed, 2016).

Table 3-2 illustrates the average monthly and annually flows in Mm^3 in both stations. It can be seen that the gauge at Falaj Al Saidi had received yearly higher discharge two times more as Al Houqain gauge. Almost, it has an average volume exceeding $4 Mm^3$ through the whole year. This is as a result of dense rainfall in this area and to the size of the wadi itself (Amerjeed, 2016). In brief, valley or plain

gauges receive the total floods before reaching to the coast and then release their flows to the sea. Generally, heavily rainfall in 1997 produced maximum wadi flow of more than 50 Mm³ (Figure 3-6).

Table 3-2: Average Monthly and Annually Wadi Flow in Two Gauge Stations

Station	Average Monthly Wadi Flow (Mm3)												Average Annual Wadi
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Flow (Mm3)
Falaj AS Saidil	4.83	4.59	4.82	4.8	4.77	4.94	4.82	4.67	4.84	4.83	4.9	4.86	57.66
Houqain	2.05	2.45	2.58	2.6	2.17	2.83	2.5	2.5	2.34	2.53	1.99	2.58	29.12

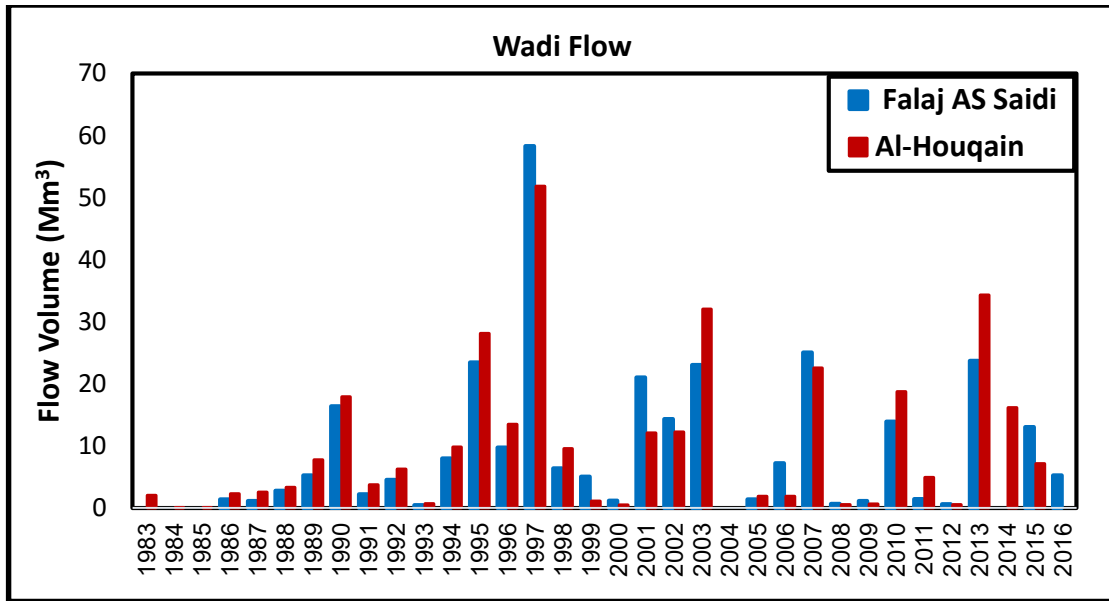


Figure 3-6: Annual Wadi Flow in Falaj Al Saidi and Al Houquain Wadi Gauge Stations

3.8 Rainfall-Wadi Flow Relationship

Figure 3-7 describes an annual wadi discharges in both wadi gauge stations with respect to rainfall records in Al Raq rainfall gauge station since all of them locate in the valley zone in the study area during different time periods from 1983 to 2016. This reflects the correlation between the precipitation event and wadi discharges. Obviously, there is a direct agreement between amount of rainfall and

crossponding flow volume. The more intensive precipitation event, the higher wadi flow can be estimated. This is clear in some tropical events as Gonu 2007 and Phet 2010.

However, most of the time of the year there is no wadi flow and they are considerably to be dry. All of this is because of the duration or sequence of precipitation event. Most of flows do not exceed days or weeks. Additionally, Wadi flows –rainfall relationship is sensitive to different parameters which play a role to the amount of discharges such as vegetation, presence of retention structure and the type of soil. After infiltration or wetting have been occurred and the porous media becomes saturated, runoff occurs. This generally happens in intensive rainfall event; otherwise low rainfall event will evaporate and no runoff can be generated (Amerjeed, 2016).

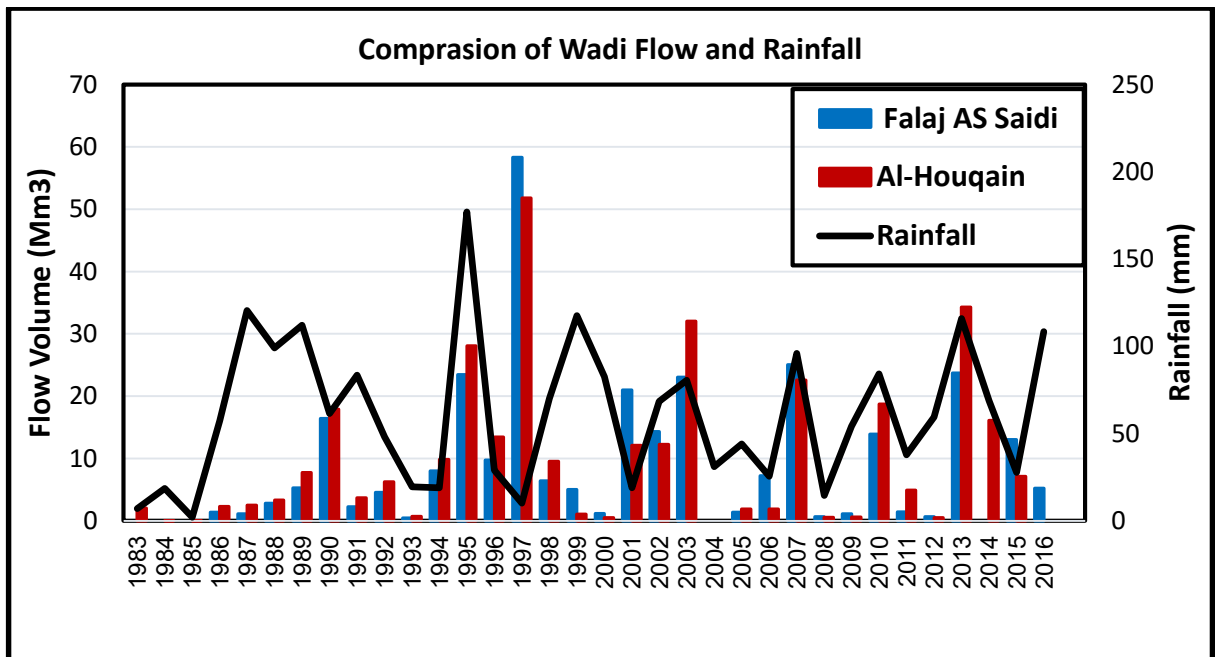


Figure 3-7: Relationship between Wadi Flow and Rainfall Amount

3.9 Groundwater Abstraction

According to (Al Barwani and Helmi, 2006; M. MacDonald, 2013; MRMWR, 2006), it was concluded that the abstraction in study area mainly occurs by wells. Aflaj

system has no significant rate of pumping and it can be neglected as seen in Table 3-3. The agricultural and hence the irrigation system in As Suwayq relies mainly on wells. Each farm has at least one well and this lead to serve extraction of groundwater in area of the study. Thus, recharge still is insufficient to recover the obtained deficit of groundwater in reference to (M. MacDonald, 2013) as observed in (Figure 3-8) . High consumption of groundwater through pumping can be found in Mabrah and this is similar to what was obtained in (OSS, 2012) that it had a deficit of 79Mm³/year. Moreover, (MWR, 2000) established a survey to explore the salinity along the coast between AS Seeb and As Suwayq. It was generally detected that area from Barka to As Suwayq suffers from high concentrated salinity with a deficit of 90.8 MCM.

Table 3-3: Consumption of Groundwater in the Study area (Mm³/year) (MRMWR, 2006)

Catchment	Area (km ²)	Agricultural		Domestic	Livestock	Industrial	Total
		Aflaj	Wells				
Mabrah	446	1.31	73.3	1.15	0.17	0.277	76.207
Ghafir	450	5.89	44.4	1.59	0.11	0.34	52.29
Total							128.50

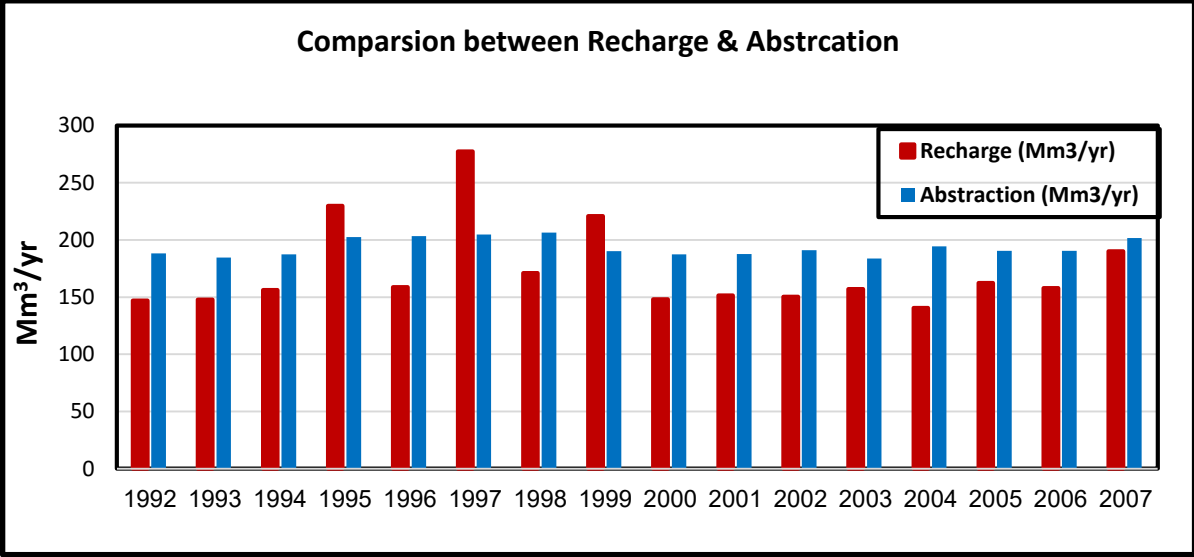


Figure 3-8 : Abstraction and Recharge in the Study Area (M. MacDonald, 2013)

3.10 Hydraulic Parameters

Based on boreholes data which is basically derived from aquifer tests conducting by consultancy companies and MMRWR. They had calculated them according to constant pumping and recovery test (Amerjeed, 2016) . It can be seen that 31% of boreholes locate in upper fars and the rest of 69% locate in alluvium aquifer. Table 3-4 shows the aquifer parameters of some borehole data which include transmissivity, hydraulic conductivity and storage coefficient.

The aquifer properties can be initially estimated through these measures. Hydraulic conductivity has a domain of 2.3 up to 33 m/day from west to east of the study area. In the same direction storage coefficient lies in a range of 0.00025 to 0.00054.

Obviously, there is no data related to storage coefficient and specific yield has only three values. The reason behind this is that pumping tests did not include observation wells which are important tools to estimate storage coefficient and specific yield (Amerjeed, 2016).

Table 3-4: Geological Properties of Borholes in the Study Area (MRMWR, 2006)

ID	x	y	Aquifer	Screened Interval (m bgl)	K (m/day)	T (m/day ²)	S	Sy
NB-17	527015	2634449	Upper Fars	-	2.3	173	0.0003	-
NB-17T	527039	634434	Upper Fars	101.26-153.54	-	19	-	-
NB-18	528417	2637063	Upper Fars	-	-	-	-	-
NB-19	524617	2630040	Upper Fars	76.91 - 116.41	-	-	-	-
NB-20	547504	2627757	Upper Fars	292.3 - 315.6	-	-	-	-
NB-21	547196	2622615	Upper Fars	95.40 - 124.40	18.4	414	0.0003	-
NB-21T	547179	2622591	Upper Fars	80.9 - 115.64	-	809	-	-
NB-22	537485	2620715	Upper Fars	-	-	-	-	-
JT-20A	536948	2615822	Alluvium	15.05-49.55	25	57	0.0005	-
JT-22	537300	2622100	Alluvium	67.0-78.0, 116.0-128.0	33	1325	-	-
G1714	527410	2642940	Alluvium	-	-	263	-	-
TW-2	517333	2626814	Alluvium	11.00 - 35.00	-	3966	-	-
G/1093	533580	2636630	Alluvium	-	-	125	-	-
BG-2	546400	2614300	Alluvium	64.98-87.91	-	1	-	-
MTW-1	522029	2636700	Alluvium	34.36 - 74.47	-	2648	-	-
JT-10	537200	2615700	Alluvium	24.5-49.0, 60-70	15	316	-	-
G1705	527230	2642570	Alluvium	-	-	202	-	-
ADG-26	548800	2632000	Alluvium	21.3-29.8, 38.7-44.8	-	168	-	-
G1937	532430	2641030	Alluvium	-	-	303	-	-
HTW-1	517607	2640771	Alluvium	19.90 to 94.00	-	4531	-	-
ADG-25	543600	2633800	Alluvium	18.9-23.8, 26.8-34.4	-	36	-	-
G-2048	524330	2643570	Alluvium	-	-	474	-	-
H-1	516558	2638681	Alluvium	35.80 to 70.00	-	2409	-	-
G1696	526920	2642620	Alluvium	-	-	180	-	-
BG-1	551200	2625700	Alluvium	19.85-48.46	-	2051	-	-
M-2	522846	2633156	Alluvium	35.60 to 92.60	-	2647	-	-
JT-20	536832	2615822	Alluvium	23-45	-	59	-	-
G1865	530820	2641340	Alluvium	-	-	344	-	-
M-1	520135	2632470	Alluvium	33.60 to 67.80	-	670	-	-

3.11 Groundwater Level Analysis

The water level of observation wells (Figure 3-4) in As Suwayq area is fluctuating based on abstraction and recharge rates. Head of groundwater is generally supposed to be high in upstream and declines gradually toward the downstream or coast. The heads of water are compared in two zones: Valley and coastal zones as the following:

3.11.1 Valley or Plain Area

Figure 3-9 explains the well hydrograph in two monitoring wells M-2 and MTW-1 in plain zone in reference to rainfall event in Al Raq gauge station. The well hydrograph of each well has large amplitude changes (more than 20 m) compared to coastal wells. This is referred to steeper hydraulic gradient in this area and corresponding geological properties.

From Figure 3-9, it is observed that both wells showing the role of intensive precipitation within three years only of 1997-1999. However, MTW-1 represents lower fluctuation of more than 20 m as M-2. This variation might be to lower permeability of southern alluvium aquifer. Similarly, it can be noticed that from year to year water head does not change (remains steady) during dry years. This is due to continuous groundwater flow that forms main input source to keep steady water table.

3.11.2 Coastal Area

The Figure 3-10 below illustrates the situation of groundwater heads in four wells: ADW-10, HTW-1, IE and Nc-10 in coastal unconfined aquifer. Generally, all wells hydrographs display small amplitude variations in groundwater head. This is correlated to high storage coefficient and uniform hydrological condition close to shoreline (Amerjeed, 2016). The long term decline in water level is associated with continuous serve pumping in coastal area. This explains that rainfall effect does not appear in recharging groundwater.

As an evidence to what mentioned above, There is a decline in head in all wells throughout last periods to about three meters below mean sea level. Likewise, the impact of rainfall during heavy storm as 1995, Gonu, 2007 and Phet did not appear clearly in term of recovery of groundwater levels. This is due to continuously excessive abstraction of groundwater using advanced machinery techniques especially in hot summer. Similarly, the absence of the role of precipitation effect in recovery of water table process is due grater depths of these wells and topography of the area since most of rainfall water goes as runoff.

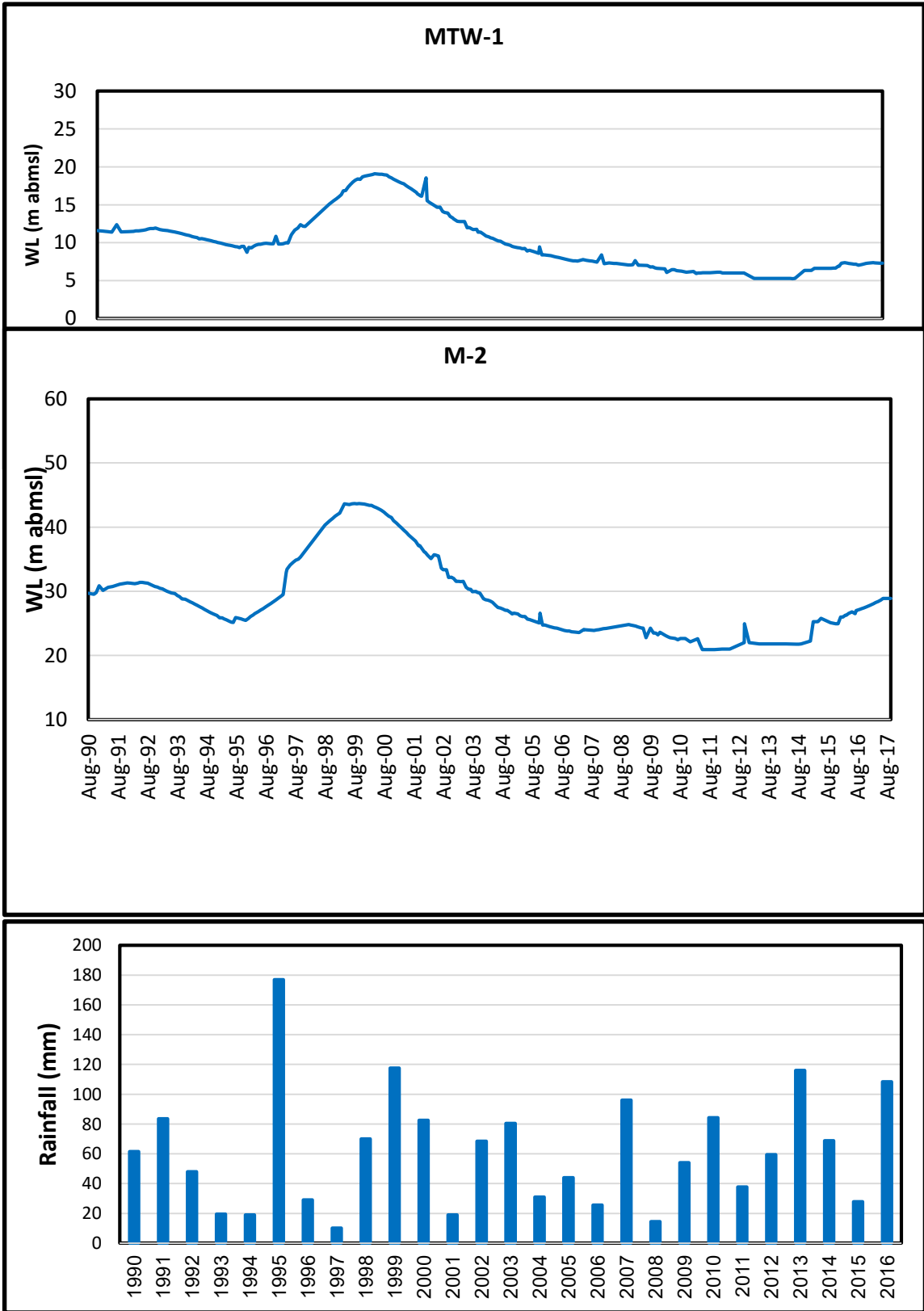


Figure 3-9: Water Levels in Valley Zone

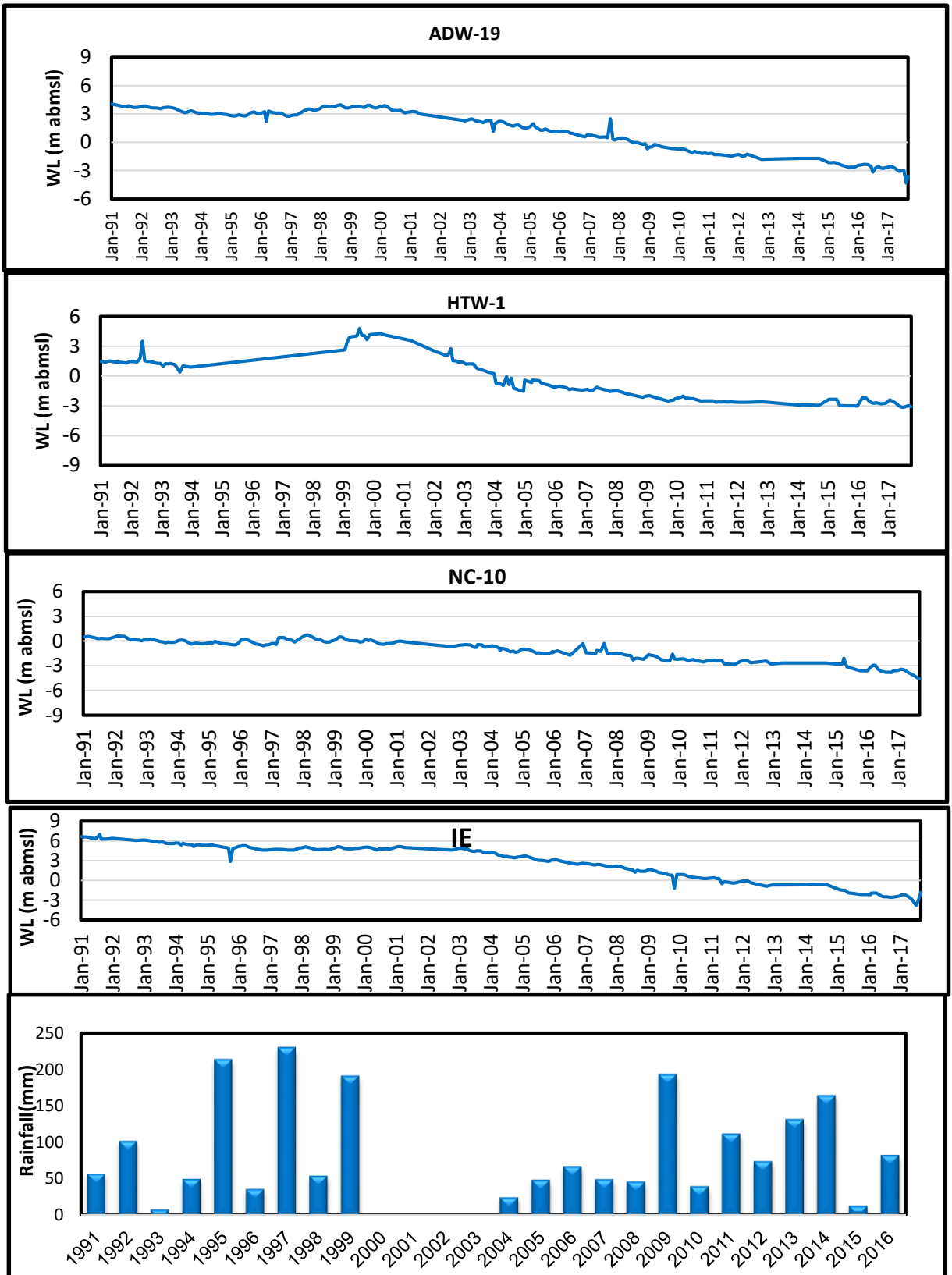


Figure 3-10: Water Levels in Coastal Zone

3.12 Quality of Groundwater in Al Batinah

Quality of groundwater is an essential issue similar as the quantity. The desired quality considers water demand purposes either for drinking, industrial or agricultural. The term of saline groundwater is applied in situation that concentration of solids in a solution greater than 1000 mg/l. The quality of groundwater for irrigation purposes contributes in the efficiency of soil and vegetation. The salts inhibit the mechanism of growth of plants through osmotic pressure or metabolic interaction and hence water limitation. Additionally, salts have reverse impacts on soil conductivity, aeration and physical structure (Todd and Mays, 2005).

The location of Oman and scarcity of rainfall result in water shortage and usage of saline water in irrigation (Ahmed et al., 2013). The total consumption of water in Oman is 1650 million cubic meters (MCM) and there is only 1260 MCM of net rainfall recharge annually. The shortage of the rest 390 MCM is provided through the groundwater discharging (Abdel-Rahman and Abdel-Magid, 1993). The dependency on the groundwater as the main source of water supply system forms large threat (Ahmed et al., 2013). Rajmohan et al. (2009) concluded that the groundwater is extremely influenced by nitrate concentration as sweater mitigate to the groundwater storage. Thus, many agricultural lands have been contaminated and lead to sharp reduction in agricultural production especially in Al Batinah region compared to the last decades.

Saltwater intrusion destructs the groundwater hydraulic gradient and allows high dense saline water to interrupt the freshwater. Also, it can destroy the hydrostatic barrier formed between fresh and saltwater. Seawater intrusion is a kind of groundwater contamination (Todd and Mays, 2005). Seawater intrusion occurs when the massive concentrated saline seawater comes in contact with freshwater. It is enhanced by the intensive groundwater abstraction (Zekri et al., 2015).

One study was initiated in some catchments in eastern of Al Batinah in 1994 including Bani Ghafer, Bani Kharous, Al Ma'awil ad At Taww. The overuse of

water resources in these areas was 151 MCM/year compared to actual annual recharge which forms only 104 MCM. For this a total deficit of 47 MCM/year was recorded through which extraction from aquifer forms 25 MCM/year followed by 16% and 6% from saltwater intrusion and interior flow in catchments (Lahey et al., 1995). It was noticed between 1984 till 2005 that the seawater interface reached to interior lands up to 12 km and this led to reduction of usage of agricultural lands to about 7% (Al Barwani and Helmi, 2006).

3.12.1 Effects of Salinity in Al Batinah

Before or in the beginning of 1970, the irrigation water from groundwater abstraction did not exceed 34 M m³/year. In 1970s, the development in the wide range of lives sectors forced farmers to start using diesel pumps to manage abstraction of groundwater. The rate of discharge enlarged in 1980s as a consequence of lands distribution policy. Providing the essential sides of settlement in term of electricity led to discharge large quantities of water and in turn caused water table delineation (MAF, 1993). Identically, the development in withdrawal facilities in Salalah after 1980s decreased the quality of agricultural water so it does not fit with the desired drinking standards (Shammas and Thunvik, 2009).

In Oman, as it is an arid country 25% of Omani people prefer to settle on Al Batinah coastal plain to exercise their agricultural and other activities even this plain forms only 10% of Oman area (Abdalla et al., 2010). The common crops grown in Al Batinah plain are alfalfa, fruit, vegetables, date palm and Rhodes grass (Ahmed et al., 2013). These crops requires large amounts of water to grow well.

Salinity caused loss by formulating its impact on the farmers by introducing one term known as farmers' loss (Zekri, 2008). This term is referred to reduction of lands productivity because of salinity as formulated through study of (Hussain et al., 2006). In addition to this, stopping the validity of some wells led to farmers'

loss (Zekri, 2008). The economic value of the area has been impacted since each year an average of 18.9 to 36 million USA\$ represent the generated loss in response to salinity (Hussain, 2005). Also, validity of more than 5000 hectares lands were degraded and 20,000 jobs were lost as an effect of salinity struggle in the period of 2006-2010 (OSS, 2012; Zekri, 2008). Identically, scarcity in water resources enables only 2.22 million hectares of lands to be valid for agricultural purposes. Consequently, the local food production does not meet the food security requirements in Oman (Ahmed et al., 2013).

Al-Mulla (2010) investigated the salt affected soil in Al Batinah particularly in AL Rumies using NDSI analysis in 1991 and 2005. They found that salinity expanded excessively to cover large areas in 2005 compared to 1991. For this, most of the lands that had been used for date palm cultivation were migrated and lost their value as income source. Other lands which still used for planting recorded continuous destruction in the production.

One research was conducted to evaluate the effect of Wadi Al Hawasinah recharged dam on elimination of seawater intrusion. Wadi Al Hawasinah dam was built in 1995 with an area of 1000 km². In this study, resistive survey was applied to see the impact of salinity in rocks. It was obtained that intrinsic permeability of rocks decreases due to saline water which have a resistivity of less than 1 Ohm. On the other hand, higher resistivity of 700 Ohm reflects of freshwater gravel aquifer. Furthermore, time domain electromagnetic (TDEM) survey was implemented to explore the intersection zone of seawater and freshwater. It was observed within a depth of 10 – 20 m the plume is directed at high rate toward the southwest (Abdalla et al., 2010).

3.12.2 Salinity Management System

The salinity would stay a critical issue that it requires careful management to at least minimize it to lower levels because the seawaters have already interrupted with the existing groundwater storage. One of the important management systems is applied through the equilibrium between annual recharge and groundwater pumping. Another tackle system is recommended by

encouragement to grow some seasonal crops and fodder instead of grasses (MAF, 1993). After 1970, the Ministry of Regional Municipalities and Water Resources (MRMWR) has started to update new strategies to treat the polluted areas through enhancing the recharge by constructing dams. For instant, a total of 34 dams had been implemented to tackle saline affected areas in Al Batinah coastal plains. Also, 21 of these dams were built to inhibit seawater intrusion. According to the purposes, dams have varieties in their length (100 -9000 m), height (5-25 m) and storage capacity (0.04 -11.4 Mm³) (MRMEWR, 2005) . To support this, it was found that water table level increases from infiltration resulted from Al Khod dam which is feed from Samil catchment. The non- contaminated or freshwater acts as a barrier to prevent salinity by shifting it downward and not allow the plume to extend more. All of these led to establish groundwater mound (Abdalla and Al-Rawahi, 2013). Trying to convince farms owners to use automated irrigation systems based on moisture content of soil is one significant solution to reduce the serve contaminant of groundwater quality in Al Batinah

The salinity was reported as enormous challenge in these areas in 1990s. For salinity replenishment, several procedures were updated. One effective policy was through cultivation of crops in winter instead of date palms which consume more water. Another alternative is using treated wastewater as an alternative for irrigation instead of groundwater (Zekri, 2008). The role of desalination enhanced the consumption of groundwater by 9%. These desalination plants were constructed to decline saltwater intrusion (Zekri, 2008, 2009). Moreover, enhancing the awareness among the farmers contributes to reduce the aggressive abstraction of groundwater. Installation of the modern irrigation technologies based on soil water content is one efficient method to save the water resources (Kalbus et al., 2016). Similarly, To reduce the impact of seawater intrusion, the abstraction from 116 wells of a total of 716 wells was stopped (Zekri, 2008).

Chapter 4

4. Model Construction

4.1 Introduction

Groundwater model attempt to visualize the dynamic systems of hydrology and geology that affect the real situation of any aquifer. These models enable this dynamic system to be solved numerically through known mathematical expressions. They are directly manage all the driving forces in term of hydrological and geological parameters.

This chapter introduce all physical parameters and how they interrupt to the model. Data inputs will followed by calibration which is essential process to come out with some future predictions.

4.2 Conceptual Model

Construction of the model basically depended on the available hydrological and geological data that have been discussed in the previous chapter. In general, the study area has a straightgraphy subdivided into four main layers from the top as follows: alluvium, upper fars, middle and lower fars. In this model, the first two layers alluvium and upper fars will be handled since the other two beneath layers are poorly impermeable. The thickness of upper fars ranges from 213 to 582 m overlying with a top layer of alluvium with a thickness of 16-50 m (Kalbus et al., 2016).

The flow in the model is predominated by distribution of recharge and discharge in the study area. Regional flow is generally influenced by the gradient in head through which is steeper in mountain areas and shallow in downstream areas. The flowing is directed from higher gradient upstream in a direction parallel to the coast which have shallow gradient (Figure 4-1).

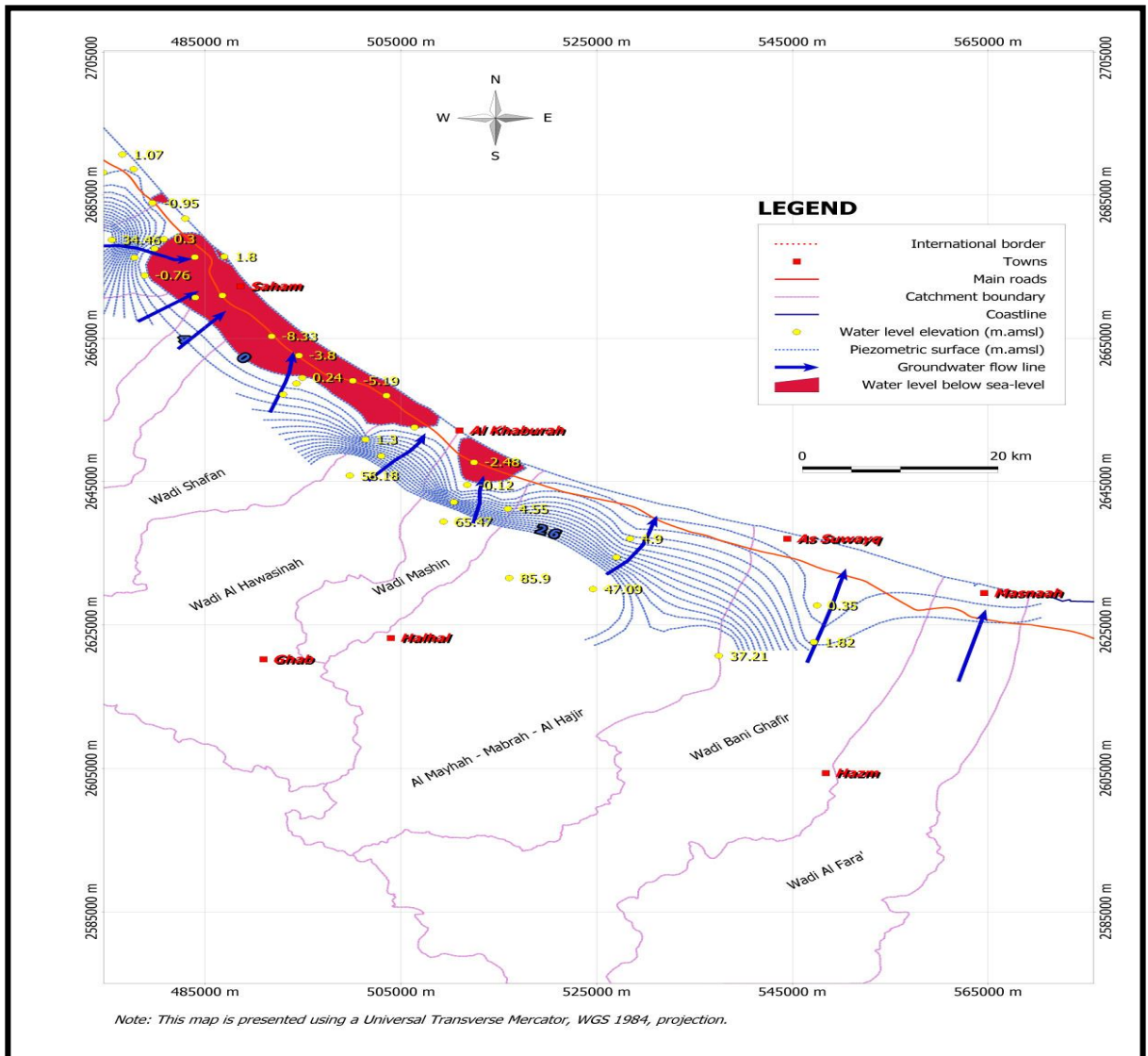


Figure 4-1: The Direction of Flow of Groundwater (GRC, 2006)

4.3 Numerical Model

(Amerjeed, 2016)The process of groundwater modeling relies on two essential components to being achieved successfully which are

1. The deepest understanding of groundwater system in terms of water balance system and this can be visualized through conceptual model.
2. Physical and observed data which are needed later on in the calibration process such as borehole data and water level in the wells.

4.3.1 Model Domain

Selection of model boundaries or study are basically depend on geological and hydrological natures in terms of available data. In this model, the focus on area where agricultural and other industrial and domestic activities concentrate more as highland lands. This are is one of the most important fertilized area in terms of the seasonal crops that have been grown yearly. For this, the model extends from 5113030 to 5546100 E and from 26172300 to 26466600 N with an area of 704 km² as seen in Figure 4-2.

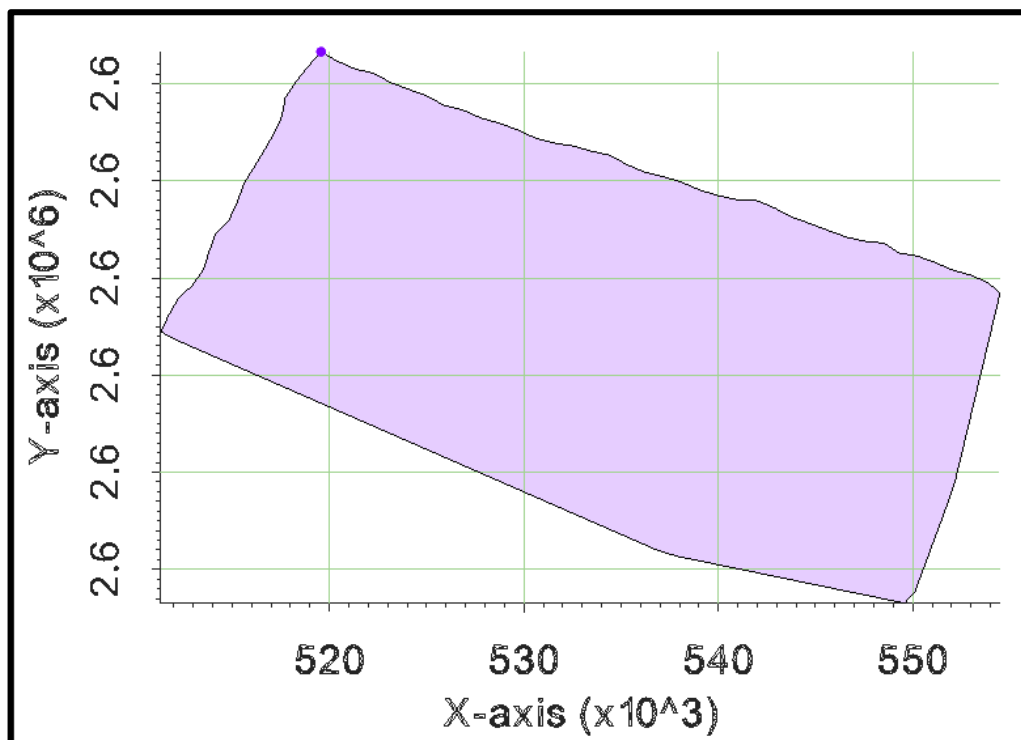


Figure 4-2: Extension of the Conceptual Model

4.3.2 Model Grid

The area is discretized through finite difference- grid system. The area is divided to square grid cells with a size of 200 m by 200 m resulting in a mesh of 85 rows and 189 columns (16065 cells per layer) and a total of 32130cells. The outside cells are considered as inactive cells (12020 cells in both layers) and are not include in the model simulation. Only 20110 cells (10055 cells in each layer) are sorted as active since they are inside the boundaries of the area.

4.3.3 Boundary Conditions

Model boundary conditions visualizes the external physical and hydrological conditions on the external boundary of aquifer (Amerjeed, 2016) and (OSS, 2012). On other hand, internal condition within the boundary reflect the hydrological conditions such as recharge, extraction and pre-defined level. For the study area, the following condition were selected:

- A constant head boundary was imposed to relief fixed or constant head. It allows an infinite flow to and from the cell in response to hydraulic gradient and hydraulic properties (OSS, 2012). It is applied at the costal boundary of the sea of Oman in the northern part of the study area. At that boundary, a specified head of zero was given to all cells locates in the two layers.
- No flow boundary is specified boundary of zero flow value. In this model, there are two no flow boundaries as shown in Figure 4-3. From Figure 4-1, it seems that the groundwater flow is directed from southern upstream to the shoreline with respect to hydraulic gradient. As a sequence, the eastern and western boundaries are assumed to be no flow boundaries. Similarly, no flow boundary can be functioned at the bottom of first layer where the groundwater is flowing parallel to aquifer base and interface (Amerjeed, 2016)and (OSS, 2012).
- General Head Boundary (Interflow Recharge): the subsurface flow or recharge from the upstream is defined as general head boundary. These quantities of groundwater recharge from Jabel are feeding the water storage. This boundary acts as input source for groundwater storage.

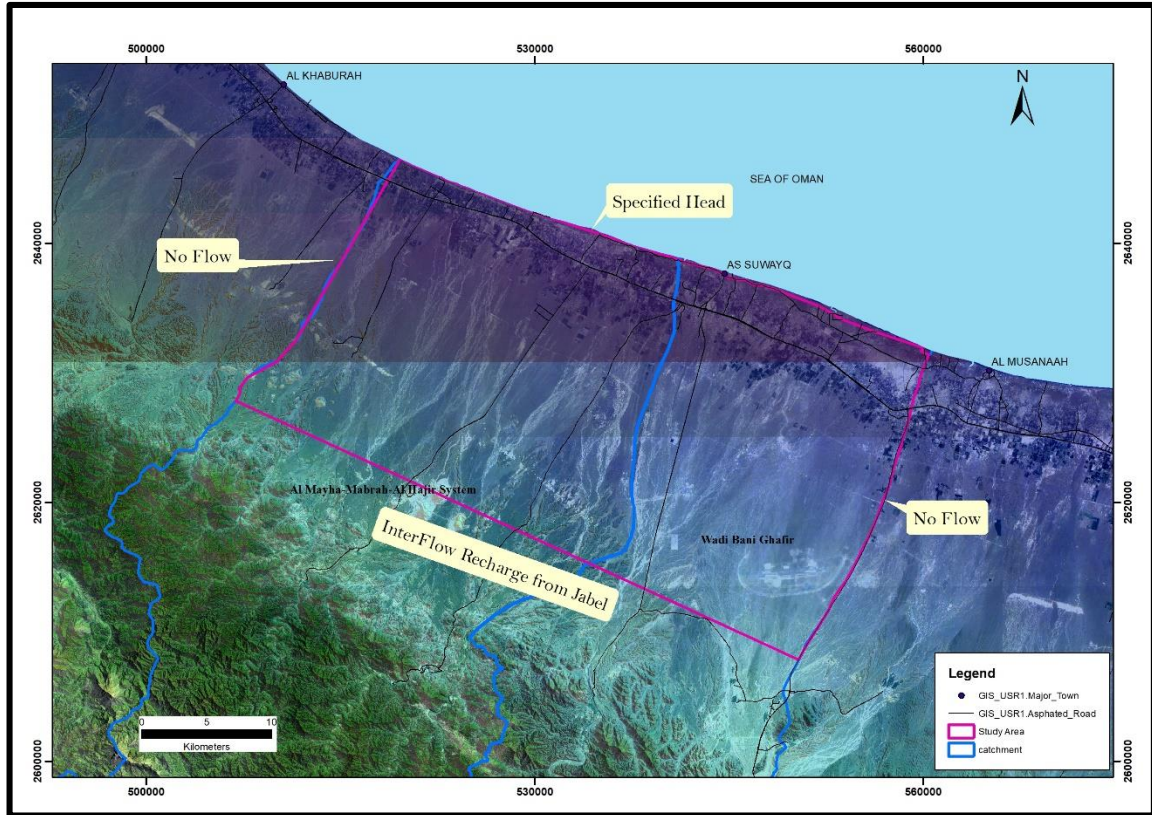


Figure 4-3: Boundary Conditions in the Study Area

4.3.4 Simulation Period and Stress

According to data availability, the majority of wells have water level date from the beginning of 1980s. Unfortunately, since the trend of head in some wells was unusual as supposed to be in terms that the head reduces toward the sea. It was found that there is no enough accuracy during the measurement of water level. All of those factors led to use recent data and start the simulation from January 2010 up to September 2017.

To see the fluctuation in water table level in different durations of time, transient model is applied to magnify the changes in heads over different stress periods. A stress period is defined as time period through which all time dependent process as recharge and abstraction are constant (OSS, 2012). It is installed in monthly basis to create a set of 95 stress periods in the whole duration of

simulation of 2010-2017. The available groundwater level data was used to construct the lengths of these stress periods.

4.4 Model Selection and Pre-Post Processing Software

Consideration of the type of the model that needs to be selected is the main essential element in the success of any modeling study. For this purpose, MODFLOW-2000 is the main technique to handle the groundwater situation in the catchments of the study area. The computation of water levels and their directions are built in three dimensional finite difference grid elements to deal with both steady and transient flow phenomena in confined and unconfined aquifers.

Groundwater Modeling System (GMS) is a computer code and it acts as pre and post processor software for MODFLOW-2000 to reveal the modeling process and viewing the output results (Amerjeed, 2016). Beside to this, GIS and Google earth are an important tools used to present the flow direction and elevations of ground surface respectively. Moreover, using of Microsoft Access software for creating data base for pumping wells sine dealing with large number of wells. It facilitates the distribution of abstraction rate throughout the stress periods.

4.5 Hydrological Framework and Stresses

The flow of groundwater and its levels are mainly affected by geological properties, boundary conditions and fluctuations in rates of both recharge and pumping. All of runoff, evaporation percolation and intensity of precipitation affect the recharge process. Also, this hydrological process is governed by aquifer properties, the wide of vegetation cover and soil characteristics. Additionally, extraction wells are clustered in plain or coastal area. The purpose of modeling process is to see the impact of all of these driving forces in the water budget.

4.5.1 Processing Layers Elevations

The setup of layers elevations is the initial component in the conceptual model. The data of the elevations of layers are imported from boreholes logs and previous investigated study (GRC, 2006; MacDonald, 1990).

As disused in Chapter 3, catchments of study area have alluvial and upper fars aquifers which showing different geological features in term of hydraulic conductivity, porosity, specific yield and specific storage. Borehole logs data from MRMWR was used to prepare cross section for the study area using borehole module in GMS. This facilitate to show the straightgraphy of aquifer smoothly

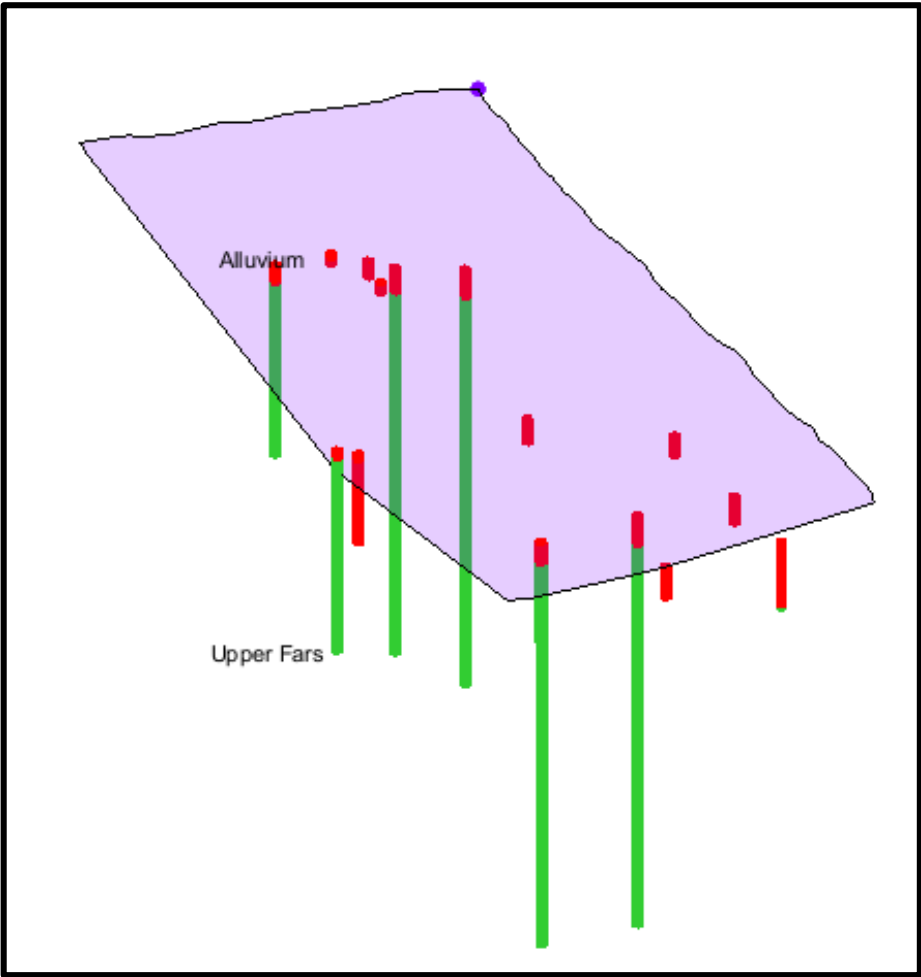


Figure 4-4: The Required Borholes for Cross Section

The lithology of the study area was shown from data of 15 borehole logs as seen in Figure 4-4 with crossponding bottom elevation of alluvium and upper fars (Appendix A). Top elevation of alluvium was checked by Google earth since it is an accurate tool to estimate ground surface elevation. This because there is a

level of uncertainties in the records of alluvial top elevations that were brought from MRMWR.

After that, the elevations of both layers were calculated with respect to mean sea level with their corresponding material as shown in Appendix A.

3D cross sections were made to see the straightgraphy of the study area and they can be constructed either manually or automatically. Then, the prepared cross section was transferred to solid by executing the Horizons to Solids command. The resulted solids can view the depth of each layer. From the solid cross section of the area of study, the thickness of alluvium locates in the range of 40-150 m and deep upper fars aquifer has wide thickness from 330-690 m (Figure 4-5 and Figure 4-6).

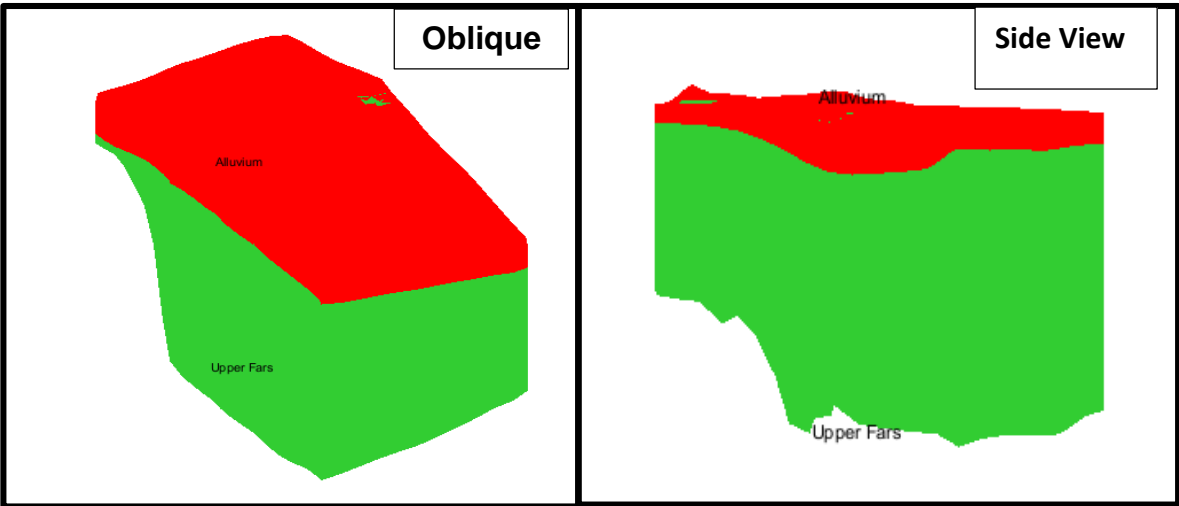


Figure 4-5: The Solid Cross Section of the Area

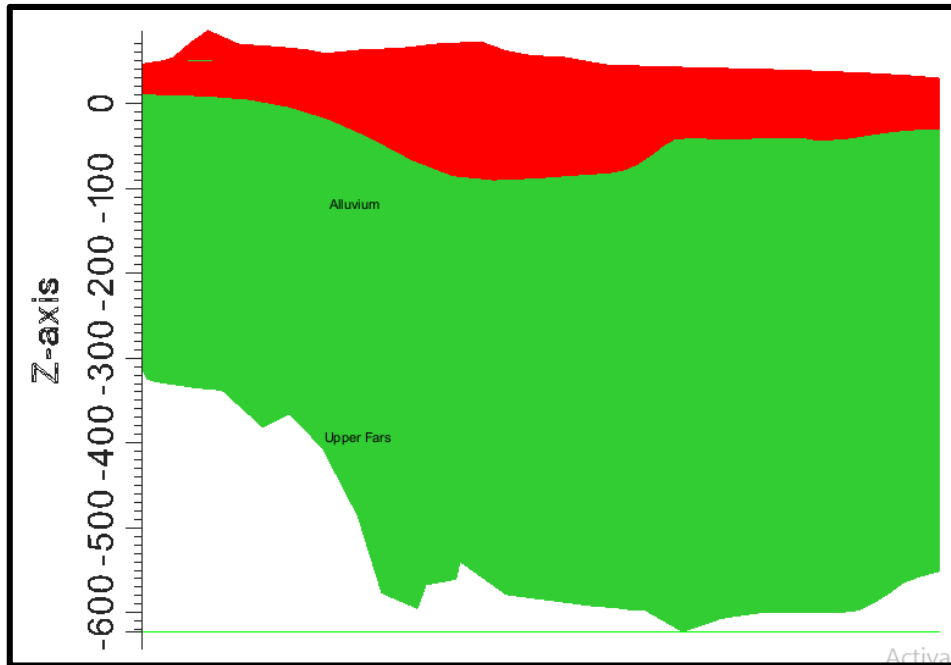


Figure 4-6: The Elevations of Alluvium and Upper Fars

The straightgraphy cross section using solid module in GMS was compared with existence cross section for Bani Ghafir (MRMWR, 2006) including the elevations of alluvium and upper fars above mean see level. Good matching was reached between prepared solid model and cross section of Ghafir catchment since it has an alluvial thickness of 41 to 106 m. On the other hand, the thickness of upper fars locates in the range of 385-560 m (Figure 4-7).

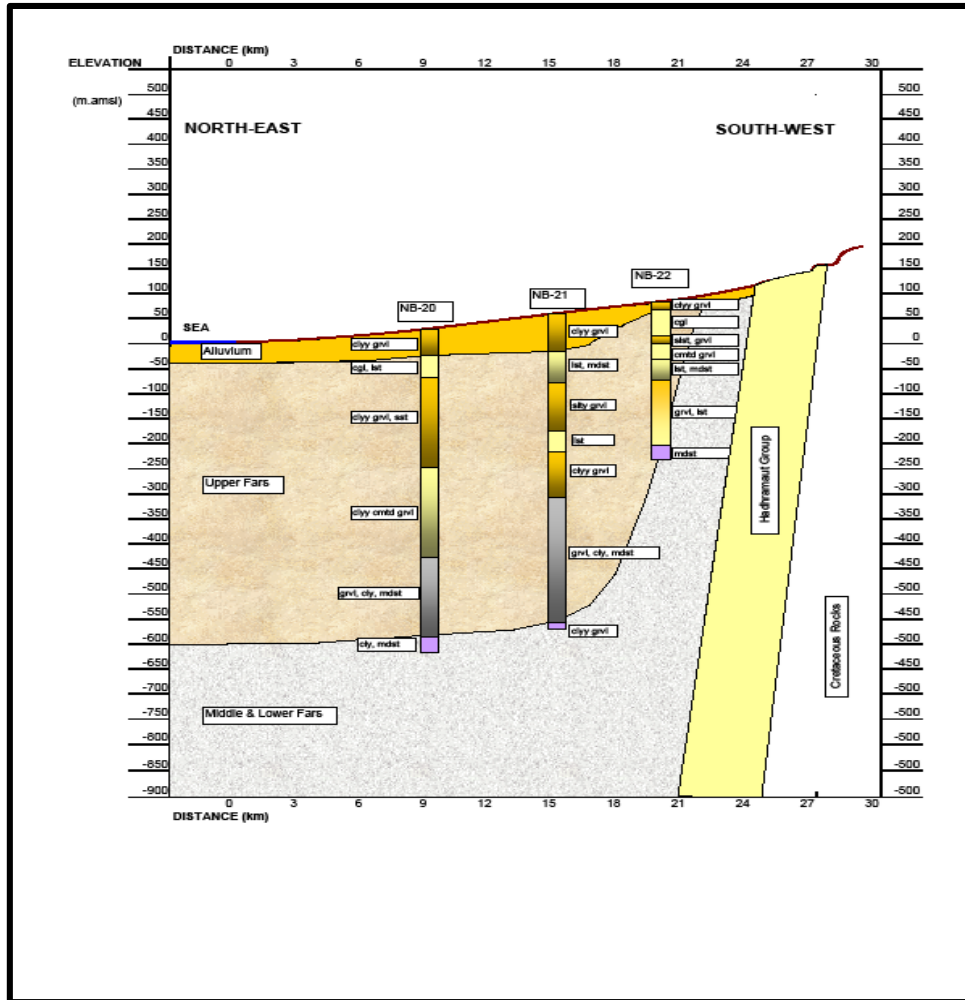


Figure 4-7: The Cross Section of Bani Ghafir (MRMWR, 2006)

4.5.2 Processing Aquifer Parameters

After the stage of layers elevations was completed, it is necessary to set up the aquifer geological properties. As mentioned in Table 3-4 in Chapter 3 that was not enough data to clarify all geological parameters considering hydraulic conductivity, specific yield, specific storage and porosity. Pumping tests for some boreholes can give an initial estimate for only two properties such as K and S_s . As discussed in Table 3-4, there is no data related to S_y and the initial data was built from (Amerjeed, 2016) study since the catchment in his study locates

nearby to the study area. Table 4-1 summarizes the initial values belong to these properties in response to borehole data from MRMWR and from (Kalbus et al., 2016) & (Amerjeed, 2016) studies. These values will be used as initial values in the conceptual model and will be calibrated later on since they play a role in the storage of groundwater.

Table 4-1: The Range of All Hydrological Properties in the Aquifer (Amerjeed, 2016) & (Kalbus et al., 2016)

Formation	K (m/day)	S _s	S _y (1/m)
Alluvium	0.5-33	0.00054	0.00028-0.2
Upper Fars	0.1-5	0.00025-.00032	0.0007

4.5.3 Processing Recharge

Recharge is considered as one of essential elements in hydrological process that have to be handled. As mentioned above, there is no forward method to estimate the amount of recharge that percolate to the aquifer since it relies on rainfall intensity and duration, soil type, vegetation cover, infiltration through wadi flow and irrigation and topography of the ground surface (Amerjeed, 2016). The direct recharge from rainfall mainly remains as the main source for recharge and it varies with elevation of the area. For this, the area of As Suwayq was divided to three zones in reference to the topography as follows:

4.5.3.1 Upper Valley Zone

Upper valley zone occupies an area of 163 km² and generally it has no agricultural activities. It has lower percentage of rainfall that contributes as direct recharge. Only 14% of rainfall represents direct recharge and the rest of water either evaporates or goes as runoff.

4.5.3.2 Middle valley Zone

Middle valley area represents higher recharge as in upper valley zone. It has a wide area of 357 km². It has small cultivation activities as can be seen from the data of discharging wells (Figure 4-8). Middle valley area shows that 15% of

precipitation can percolate to the main aquifer as direct recharge. The rest of 85% similarly will flows as runoff and evaporate with moderate to high temperatures.

4.5.3.3 Coastal Zone

Coastal or plain zone has large number farms and there is high rate of abstraction as a sequence that too many wells are clustered in this area. It forms a total area of 166 km². Uniformity of the ground surface, well sorted soil and homogeneity of the aquifer in this particular area close to sea lead to a rate of 18% of rainfall is percolated as recharge. The remaining percentage will be lost in term of both flooding and evaporation.

4.5.4 Processing Interflow Recharge from Jabel

Assequence that the upper boundary was considered as general head boundary, this means that amounts of groundwater flows from mountains toward this boundary to feed the storage. Its role will be more clearly in the wells in the same area. Initial heads were determined based on water levels of observation wells locate at or close to the upper boundary. For the transient simulation, the head was entered in monthly basis as a step graph function. To achieve water balance in term of inputs and outputs, calibration is installed to give better match between simulated and observed data.

4.5.5 Processing Abstraction

Beside to recharge and lithology of the area, discharge acts as one effective parameter that affect the water balance in the study area. The concentration of these wells can be found in lower coastal catchment area due to the uniform soil size. Excessive abstraction results in seawater intrusion due to negative gradient that allows seawater to intrude instead of flowing of groundwater to the sea. The most rate of abstraction is resulting from wells as compared to aflaj system as discussed in chapter 3 where people rely on wells more than aflajs which represent small percentage of output and even can be neglected. There is no available date showing the pumping rate from wells.

For the modeling purposes in this catchment area, inventory wells project that was installed in 1992 is used as the main source of data. The rate of abstraction was given as an average in L/sec. According to national wells inventory (Figure 4-8), there were 1587 wells with an average rate of discharge of 471 m³/day and a total of 273 Mm³/year. Also, that the discharge in Jahawir catchment ranging from 0.2 to 76 L/s which is relatively higher than Bani Ghafir catchment with a range of 0.4-16 l/s.

In the steady state the average rate is used as it is in 1992 in m/day. In transient, the value of pumping is assumed to be the same as 1992 since there is no records for pumping in these years. The average value for each well is divided among the stresses periods through which the total pumping rate in all the stress periods for any year shall equal the average pumping rate within that year.

The distribution of abstraction rate in all stress periods was established in reference that in winter the decrease in water head is less than summer times as observed after analyzing wells data from 2010-2017. The pumping rate was distributed among four periods in each year; two in winter and two in summer. As a result, it is assumed that discharge rate in winter time decrease by certain percentage and this amount is compensated during hot summer as seen in Table 4-2. For example during January to March, discharge decreases by 60% so only 40% will form the remaining rate. This decrease will be added to abstraction rate in summer to be 160% from April to June. Dealing with too many wells is tedious work so coding or programming was functioned to deal with this abstraction data to calculate the rate of abstraction in all stresses periods. Access was requested to do all of these calculations as seen in Appendix C. Later on and because there is no real measured records for discharge and due to presence of a range of uncertainty in these measurements, calibration of abstraction is an essential step to balance the groundwater storage.

Table 4-2: Seasonal Distribution of Pumping

Period	Increase or Decrease Percentage (%)	Remaining Percentage (%)
January -March	Decrease by 60	40
April-June	Increase by 60	160
July-September	Increase by 70	170
October-December	Decrease by 70	30

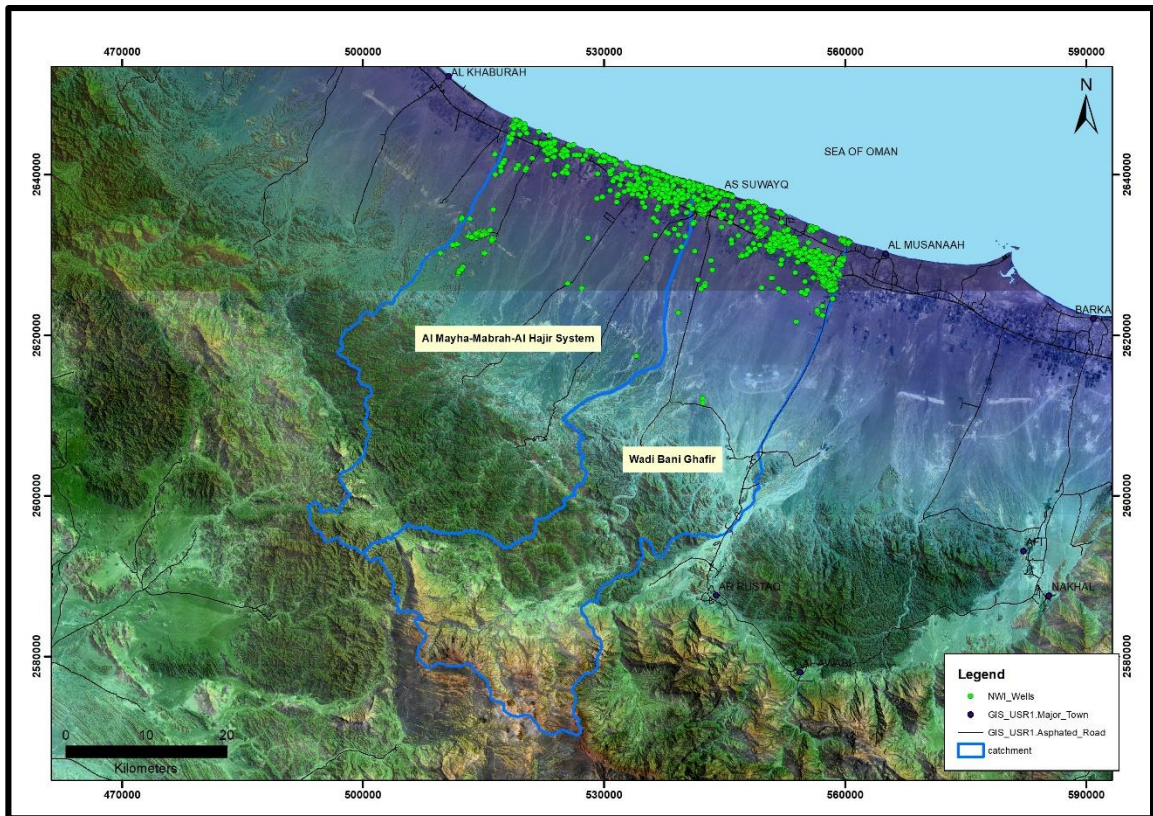


Figure 4-8: Inventory Wells in the Study Area (1992)

Chapter 5

5. Numerical Groundwater Results

5.1 Model Calibration

Non-availability or uncertainty of geological and hydrological data involves adjustment or improvement of simulated data in order to match observed values. This process is called model calibration. Initial data that were assumed as inputs and were uncertain need to be improved through calibration. Calibration of the model compares the computed and measured data and see to what extent they fit together. Calibration of the model mainly depends on trial and error to adjust the computed conditions to be close to real or observed condition (Figure 5-1).

In groundwater hydrology the simulated heads require to be calibrated with heads from monitoring wells. This procedure implies calibration of some hydrological parameters such as recharge and hydraulic conductivity. In every time run some alteration is conducted to these parameters and the model is run until computed heads fit with observed heads of the aquifer within an acceptable level of accuracy. In GMS the calibration is installed through minimizing the residual error that is indicated by target bars. The objective in calibration process is to obtain the lowest errors based on adjustment of some concerned parameters as recharge, hydraulic conductivity, specific yield and specific storage. Also, the effectiveness of the model to install further predictions was measured through three main performance criteria which are mean error (ME), mean absolute error (MAE) and root mean square error (RMSE).

It involves an assumption of steady state and implements the initial conditions to evaluate the piezometric head in the area of aquifer. The best trend between computed and observed measures is obtained by modifying some factors such as recharge through infiltration and hydraulic conductivities of the aquifer. When the best agreement between observed and simulated heads in steady state model is confirmed, the computed head will be considered as initial head for transient

flow computation. Both steady state and transient have the same hydraulic conductivity inputs. Conversely, the initial boundary conditions are governed by steady state model compared to transient model through which recharge process is managed (OSS, 2012) .

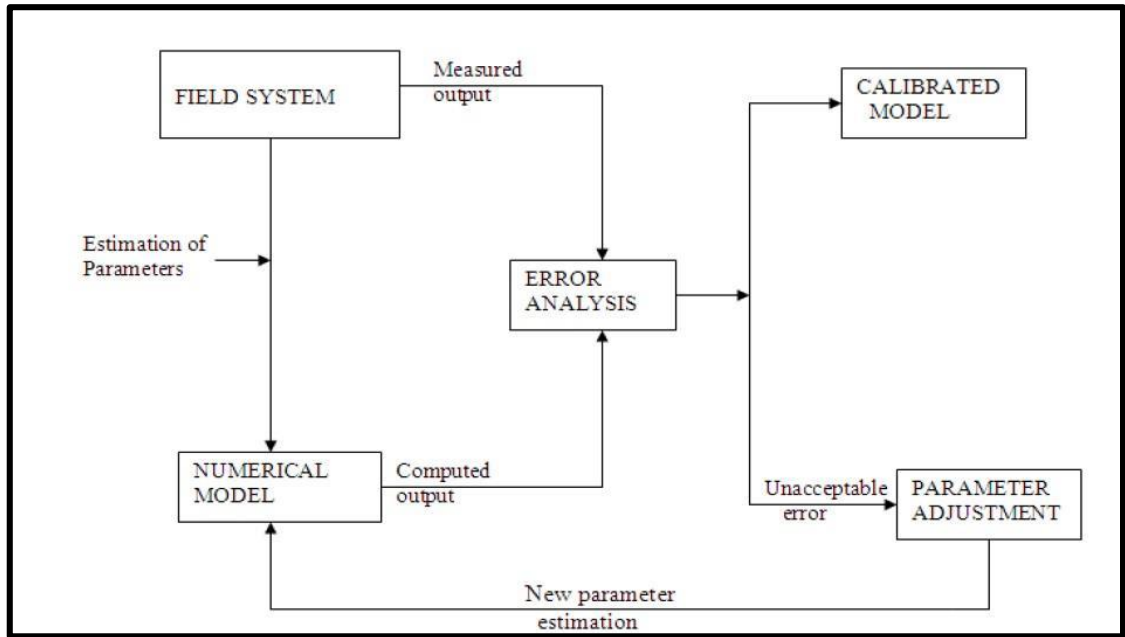


Figure 5-1: Trial and Error for Calibration (Anderson et al., 1992)

5.2 Steady State

5.2.1 Parameters Calibration

After the stage of data inputs has completed for one year simulation period in steady state condition, the model will run for one time step. Then, the computed water levels will be compared with observed ones. The adjustment of the computed heads will come in term of calibration or adjustment for the most sensitive parameters. After the best match between observed and computed heads is obtained, simulated heads will be functioned as initial heads for the transient flow simulation.

Due to non- accuracy of some measured water levels data, the optimal trend of heads was found in data of 2014 to confirm it for the steady state condition. However, discharge data as mention in previous chapter are uncertain since they

were measured in 1992 during national wells inventory project. Consequently, abstraction rates were calibrated to find the actual rate in 2014. For the remote area from the coast, the important parameter to be calibrated was groundwater flow from Jabel. Addition to abstraction rates and groundwater flow from the Jabel, hydraulic conductivity was calibrated to get the real properties of the aquifer.

As seen in figure, the calibration includes nine observed wells within an interval of 2 m accuracy (Table 5-1 and Figure 5-2). It is noticed that the wells close to upper boundary are affected by altering groundwater recharge from Jabel. On other hand, the abstraction is mainly responsible for water level changes in the wells located at downstream boundary. To calibrate the hydraulic conductivity, the area was divided to six zones with different K values and it was found that K value of alluvium increases from west to east (Figure 5-3). Similarly, higher K is obtained at coastal zone in contrast to upper zone as a result of well sorted accumulated sediments of uniform size. Overall, K value ranges from 1.5 to 30 m/day as described in Figure 5-3. There is no variation in hydraulic conductivity of upper fars and it has a value of 0.9 m/day. This indicates that the second layer is impervious aquifer as compared to alluvium and because all the wells settle in alluvial aquifer.

Table 5-1: Calibrated and Observed heads in 2014

Well	Observed Head (m)	Computed Head (m)	Residual Head (m)
M-1	36.18	37.75	-1.57
M-2	21.80	21.63	0.17
ADW-19	-1.70	-0.81	-0.89
MTW-1	5.30	6.74	-1.44
NC-10	-2.66	-2.84	0.18
IE-shallow	-3.40	-2.71	-0.69
HTW-1	-2.92	-4.75	1.83
H-1	0.05	-1.15	1.20
IE	-0.65	-2.63	1.98

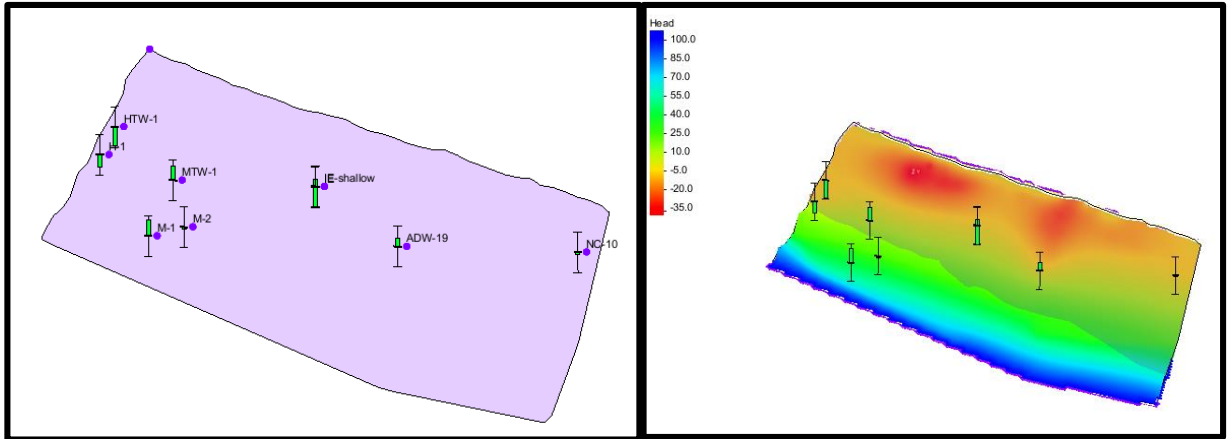


Figure 5-2: Calibrated Groundwater Heads (2014)

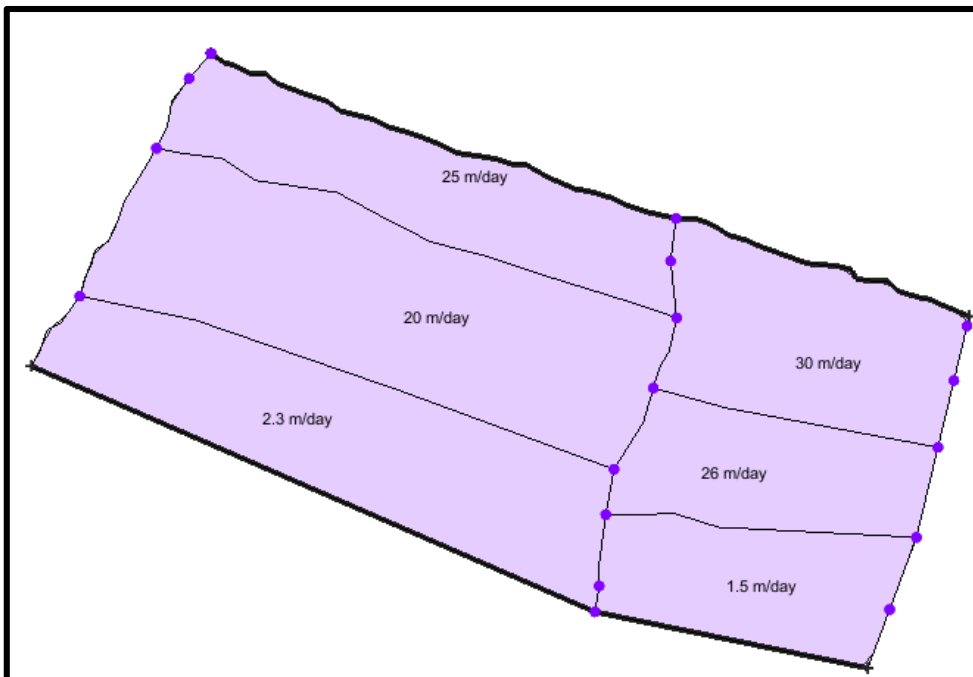


Figure 5-3: Calibrated Hydraulic Conductivity (2014)

5.2.2 Calibration Evaluation

It was found from the model properties that the model is reasonably working well with mean residual error (MRE) of 0.09, Mean absolute residual error (MARE) of 1.11 and root mean squared error (RMSE) of 1.27. Generally, the simulated heads are almost close to observed values as illustrates in Figure 5-4 since it shows very good correlation among observed and computed heads ($R^2 = 0.993$).

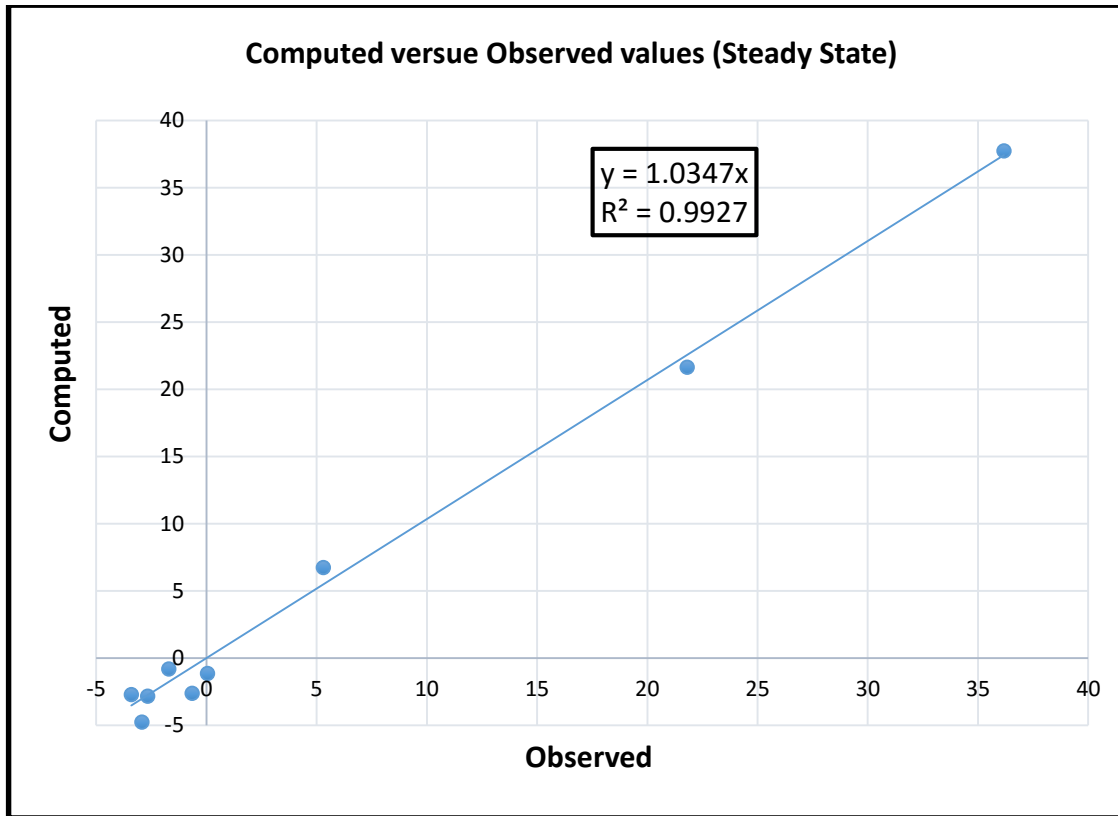


Figure 5-4: Correlation between Computed and Observed Head Values (Steady State)

According to water budget, it is obtained that all groundwater recharge from the Jabel and from low direct infiltration from rainfall is consumed as abstraction. There is no water flowing toward the sea. The opposite can be seen since the seawater intrude toward the study area. This indicates the existence of sea water intrusion due to excessive pumping. This approach fit with findings of (OSS, 2012), (Kalbus et al., 2016) and (Al Barwani and Helmi, 2006) that this area suffer from serious salinity with the largest deficit in storage of about 79 Mm³.

5.3 Sensitivity Analysis

Sensitivity analysis is an essential step to evaluate the ambiguity resulted from uncertainty of some concerned parameters of the aquifer, boundary condition and stress in the calibrated model (Anderson et al., 1992). It is relied on quantifying the parameters that have more impact in the calibration process or even future predictions of the model.

In this study, the sensitivity analysis was applied manually to detect the resulted changes in the calibrated model of steady state after alteration of some parameters, namely hydraulic conductivity, interflow recharge, direct recharge from rainfall and discharge. Each parameter was taken individually with different multipliers to visualize its statistics on the calibrated model and keeping other parameters fixed. The sensitivity analysis was implemented as mentioned above to abstraction, direct and groundwater interflow recharges and hydraulic conductivity and see the response of RMSE according to the changes in these parameters as seen from Figure 5.5 to Figure 5-8.

It is clearly seen that the sensitivity of abstraction and groundwater recharge are higher (Figure 5-5) than hydraulic conductivity of alluvium and direct recharge (Figure 5-6 & Figure 5-7). Consequently, the variation in RMSE values in the first case (abstraction and groundwater recharge) are more significant than its values generated from alteration in hydraulic conductivity of alluvium and direct recharge. This can prove that upper boundary is impacted by groundwater recharge and the down one is directly affected by daily extraction of groundwater. The hydraulic conductivity of upper fars does not have any significant response as in alluvium since all the wells locate in alluvium aquifer. For this the k value for upper fars is kept to be constant as 0.9 m/day during the whole simulation. In addition to this, direct recharge variation does not impact the calibrated model since it has closed range of resulted RMSE (Figure 5-7). The smaller or absence role of direct recharge can be correlated to scarcity of rainfall and shorter rainfall duration. For this, only smaller percentages of precipitation can contribute in recharging phenomena to feed groundwater storage.

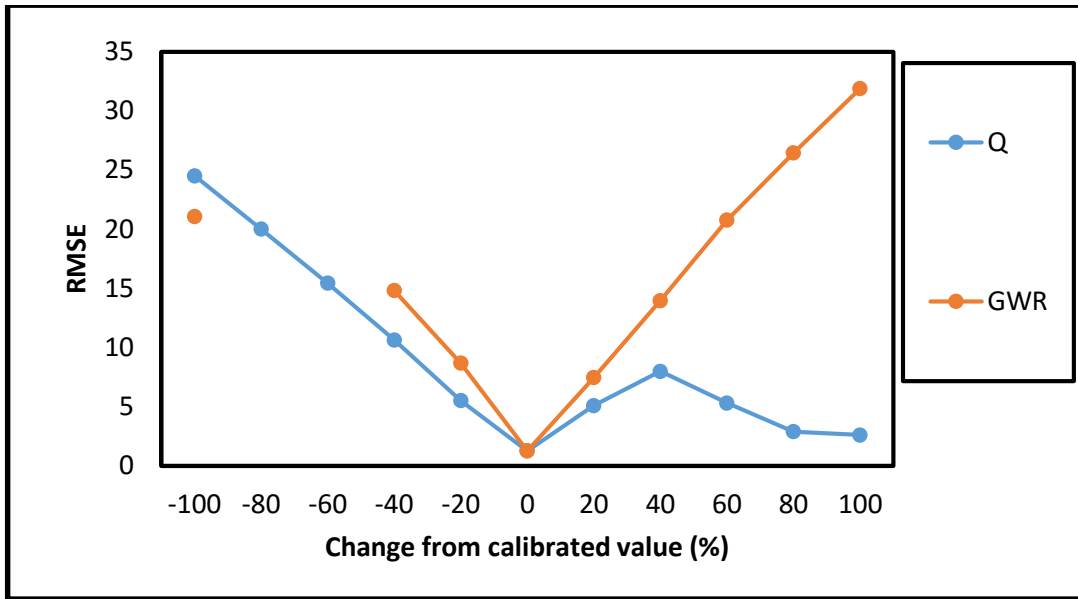


Figure 5-5: Sensitivity of Groundwater Recharge and Abstraction Parameters

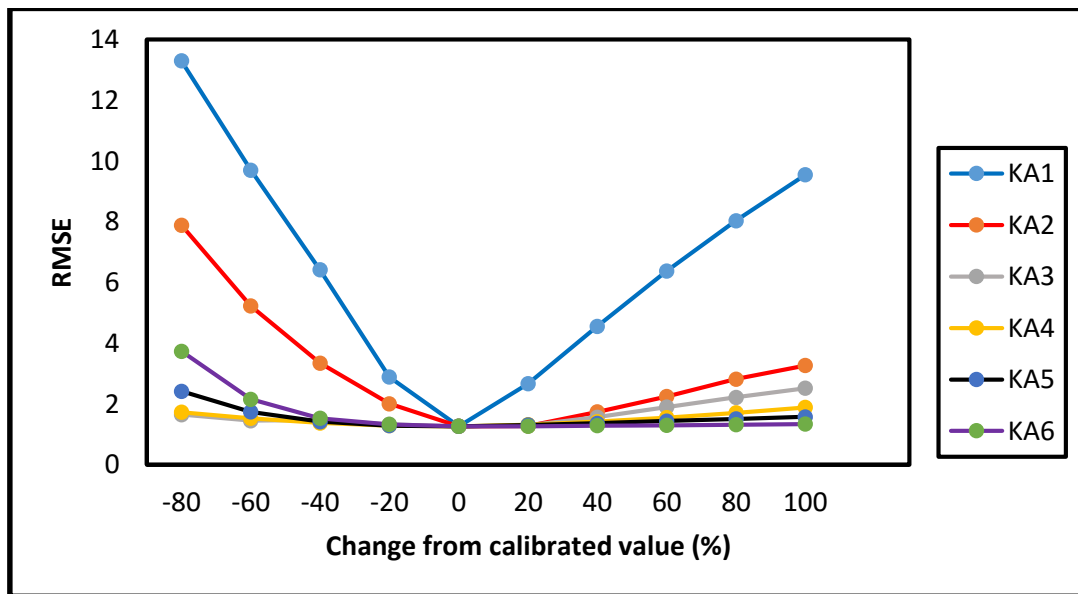


Figure 5-6: Sensitivity of Hydraulic Conductivity of Alluvium

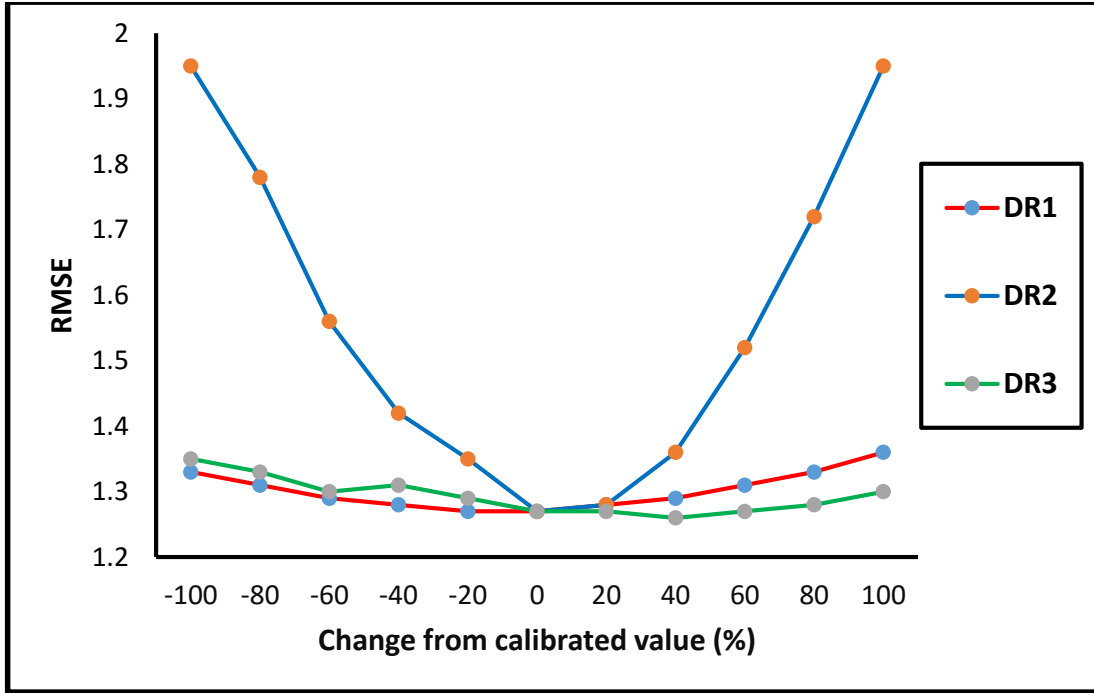


Figure 5-7: Sensitivity of Direct Recharge

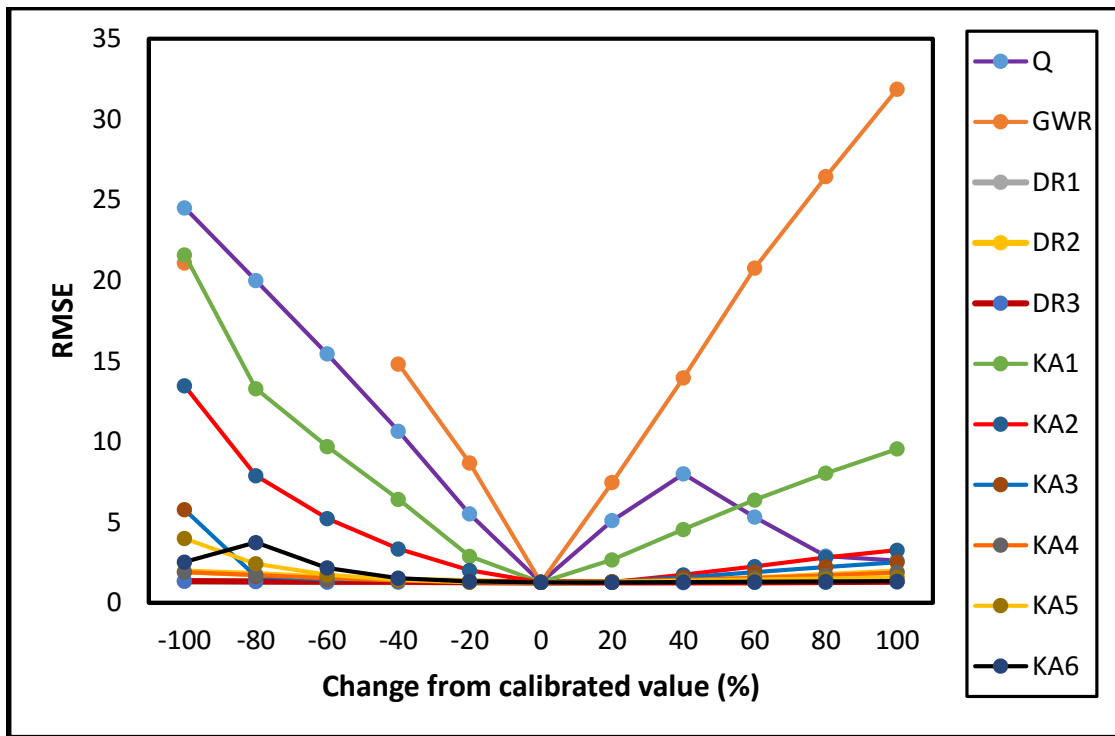


Figure 5-8: Sensitivity of All Parameter

5.4 Transient Model

5.4.1 Parameters Calibration

The computed heads in December 2009 (Steady State Simulation) as described in Figure 5-9 is used as initial heads to start the transient simulation in monthly stresses periods basis from January 2010 to September 2017 (95 stress periods). The prepared date was divided into two group sets, calibration over a simulation period of January 2010 till December 2014 (61 stresses periods) and validation over a period of January 2015 to September 2017 (34 stresses periods).

Trial and error was imposed to calibrate the transient model system by controlling the most effective parameters similar to steady state which are groundwater interflow recharge from the Jabel and abstraction. It is observed that the rest of hydrological parameters as direct recharge from precipitation, specific yield and specific storage do not affect the fluctuation of groundwater levels in contrast to sensitive parameters. All of these parameters were calibrated to obtain simulated heads within an acceptable accuracy of 2 m as maximum residual error.

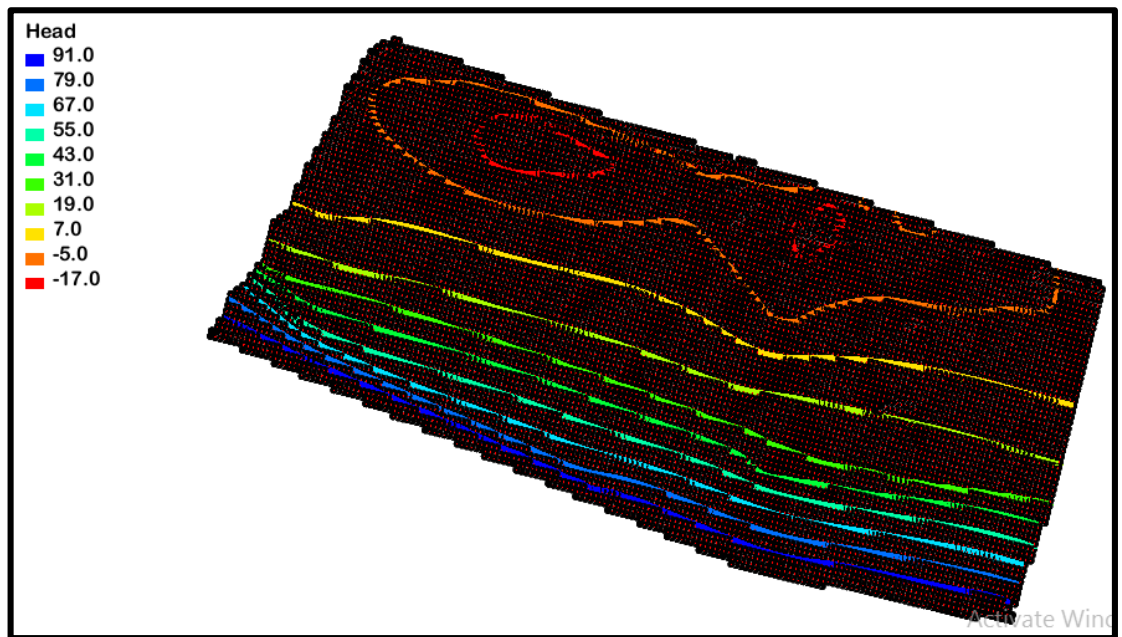


Figure 5-9: Resultant Head for the Steady State Simulation (2009)

5.4.2 Wells Hydrograph Calibration

The model was calibrated in a period of five years (January 2010 to December 2014) to monitor the changes in water levels after each month. This was achieved through calibration of groundwater recharge and discharge. In general, there is a good match between observed and computed heads. However, some deviations from observed head can be noticed in some wells and this reflects the uncertainty in field measurements and abstraction rates. Also, this can be due to ignoring of unsaturated zone in the modeling process (Amerjeed, 2016).

Overall, the transient simulation represent the fluctuation in water levels in steps of time. Figures 5-10 to Figure 5-11 explain the happened changes in heads in three wells, namely M-2, HTW-1 and NC-10 locate in highland, valley and coastal area respectively. Commonly, a trend of declining head can be observed in these wells and this is incorporated to continuous excessive pumping and insufficient recharge to recover the continuous decrease in head. The drawdown can be clearly seen in costal wells as NC-10 (Figure 5-10) through which the water level decreases to more than 4 m below mean sea level. The decline in head does not stop only to the wells located at the coastal line hence the seawater intrude to remote area from the sea as HTW-1 (more than 6 km far away from the coast) to compensate the decrease in water level due to aggressive abstraction. On the other hand, the upstream area and in the absence of discharge wells the head is generally higher and it seems to be constant. This is as a result of groundwater recharge from Jabel as M-2 (Figure 5-11). However, this well has data only up to 2012.

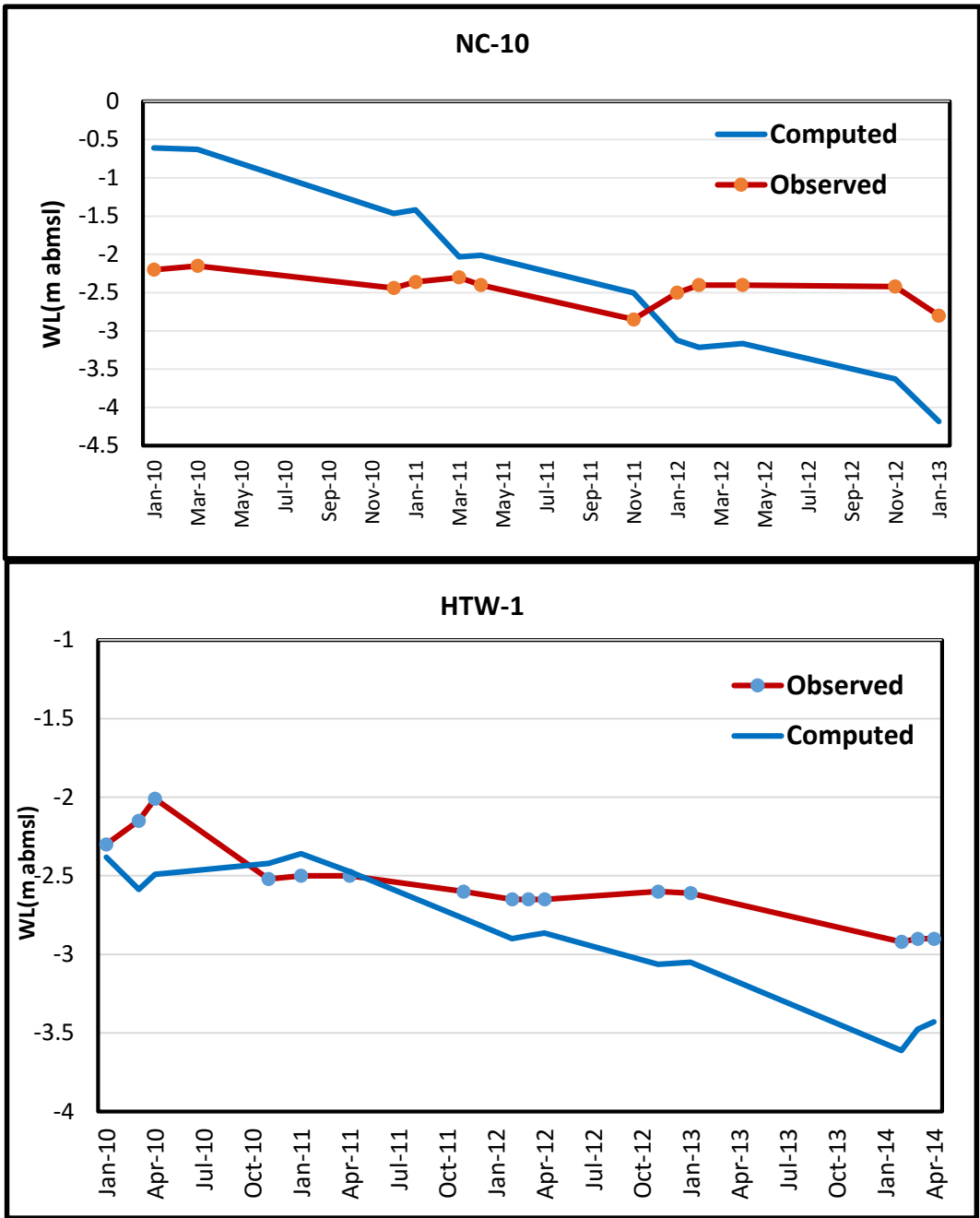


Figure 5-10: Computed and Observed Heads for Wells in Coastal Area (2010-2014)

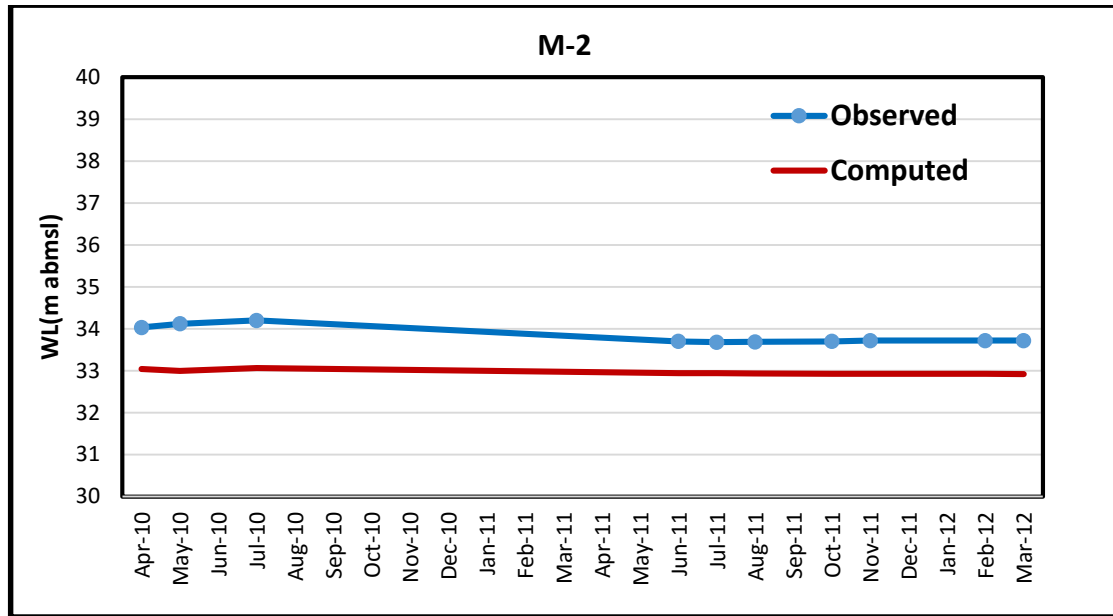


Figure 5-11: Computed and Observed Heads in Upstream Area (2010-2014)

5.4.3 Transient Calibration Evaluation

Calibration process is beneficial tool to manage the target which is the hydraulic head. This target is adjusted through adjustment of the sensitive parameters and achieving the correct water balance in term of inputs and outputs. To measure the success of the model, it is important to visualize the strength of the relation between actual and calculated heads. The distribution of the scatter points in Figure 5-12 shows good agreement between actual and simulated heads with correlation coefficient of 0.977. In terms of the resultant residual error within a limit of ± 2 m as maximum acceptable range of accuracy, the performance of the model is reasonably good. The evaluation comes with 1.35, 3.07 and 4.7 as a measure for ME, MAE and RMSE respectively.

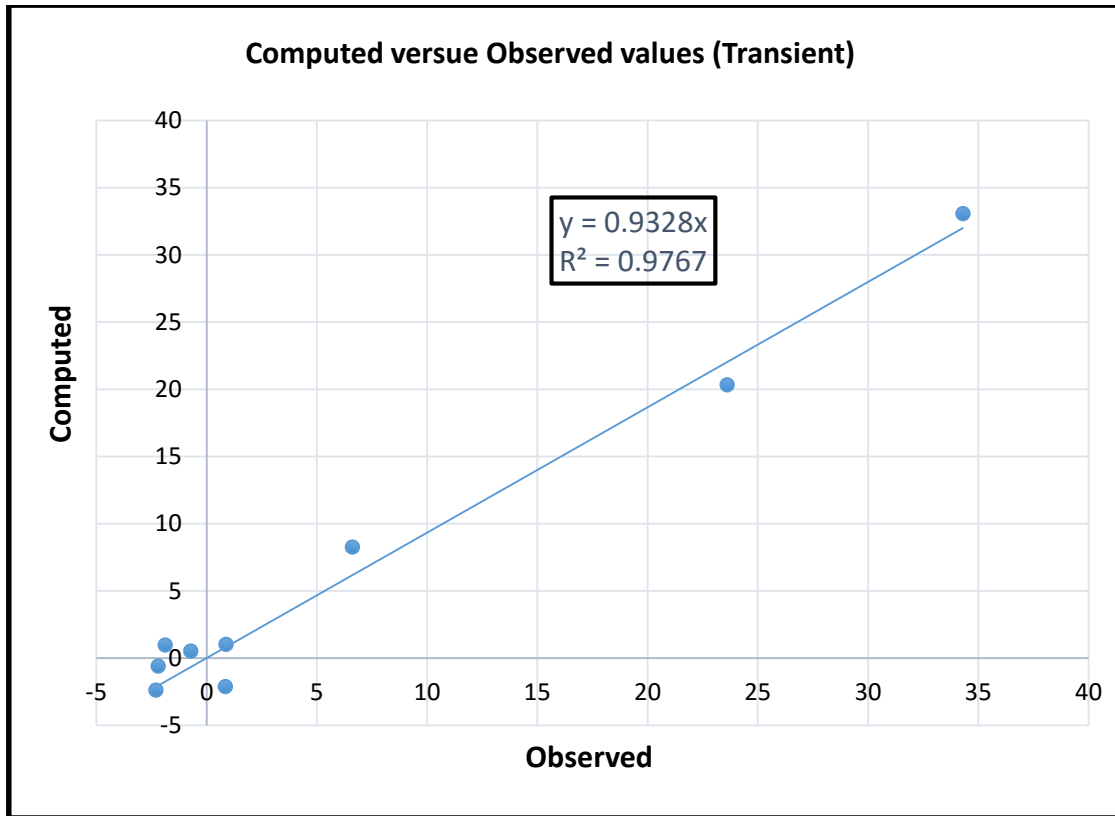


Figure 5-12: Correlation between Observed and Computed Heads (Transient State)

5.5 Validation of the Model

Model Validation is an extension of calibration process with new duration of time to ensure that model can emphasis all the changes in conditions and variables of the model. The model was validated in a time period of January 2015 up to September 2017 (34 monthly stresses periods). The resulted hydraulic head from calibrated model in a period of January 2010 to December 2014 was used as initial head for validation process. Due to uncertain abstraction and groundwater interflow recharge, initiating validated model still requires calibration of these inaccurate parameters.

After calibrating the model with new stresses periods, the model was evaluated to see its efficiency and compare it with the calibrated model. It was found that the validated modal has mean absolute error (MAE) of 3.51 and root mean square error (MRSE) of 5.32. It is obviously seen that mean absolute error of the validated model is slightly higher than the calibrated model.

The figures below reveal the obtained agreement between observed and simulated heads. Similar to calibrated model (January 2010 to December 2014), for the wells in coastal zone, there is continuous decline in head as in HTW-1, IE, NC-10. The water level continues to go down as a result of huge abstraction in this area (more than 3 m below mean sea level). In contrast to this, groundwater interflow recharge maintained the head to be steady from 2016- September 2017 as seen in M-2 and MTW-1.

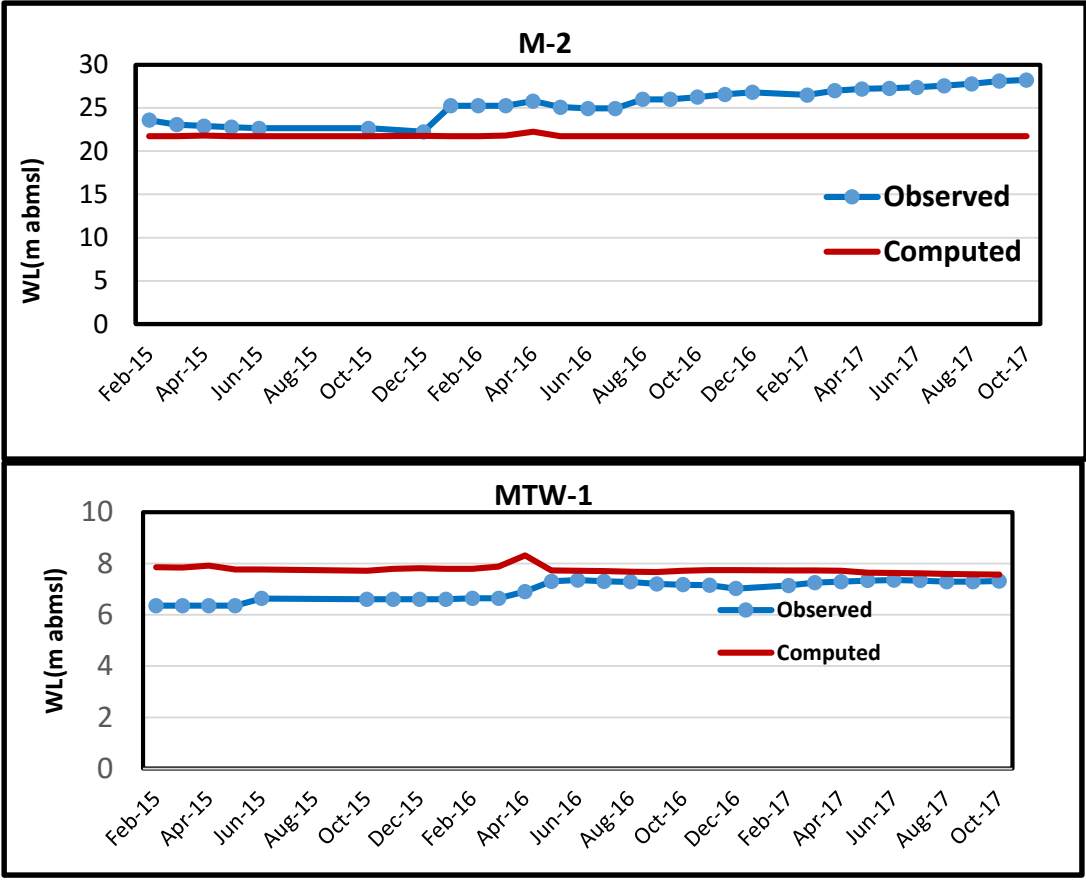


Figure 5-13: Computed and Observed Heads in Upstream Area (2014-2017)

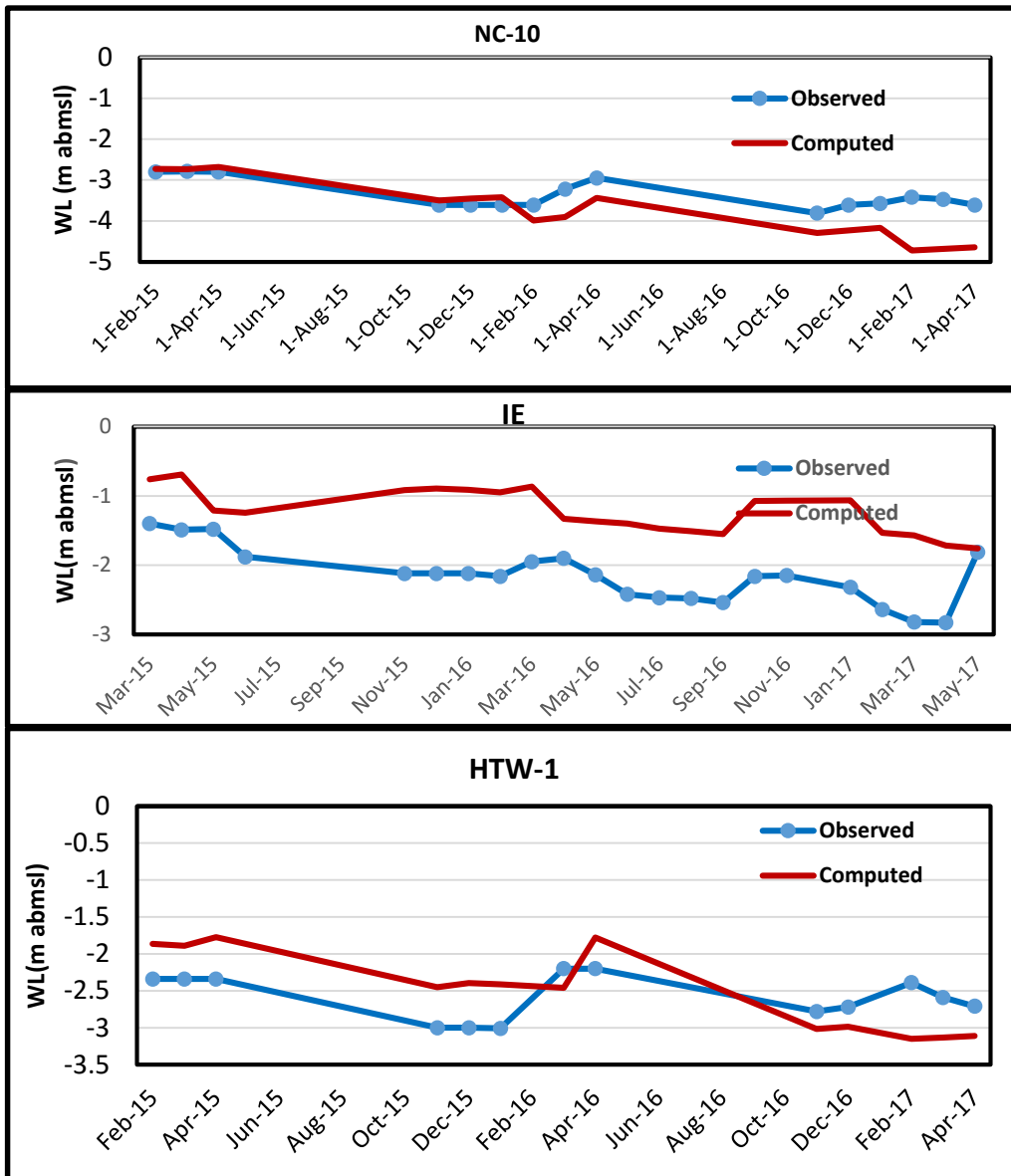


Figure 5-14: Computed and Observed Heads in Coastal Area (2015-2017)

5.6 Water Balance

As seen from Figure 5-15 below that the recharge is insufficient to meet higher demand through over pumping from the storage. However, interflow from Jabel represents the main input source for recharge but still does not meet higher consumption through abstraction. This resulted long term seawater intrusion and thus salinity which led to unacceptable quality for cultivation process. By 2017,

more than 300 MCM forms the total deficit in the area. For this plan management policies have to be installed to tackle the impacted saline water and soil together. According to (OSS, 2012) that this area has the biggest impact of salinity, the obtained deficit of above than 300MCM fit with (Abdel-Rahman and Abdel-Magid, 1993) since the total deficit is about 390 MCM in north Batinah. This mean that the majority of deficit occurs in this area.

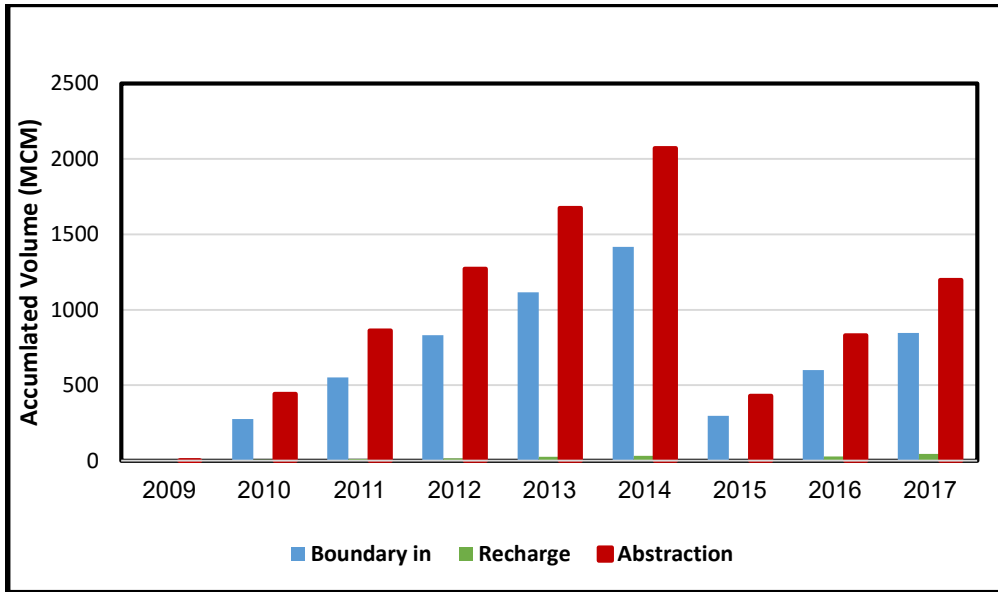


Figure 5-15: Water Balance in the Study Area

5.7 Model Prediction

To see the sustainability of groundwater, five future predictive scenarios were developed from the calibrated model (January 2010 to September 2017) for further different duration from October 2017 to 2035. The obtained results from these scenarios through the next eighteen years will be evaluated in terms of water head and water budget. These predictive scenarios will be listed below as follow:

Scenario1: Fixing all parameters as usual without intervention (business as usual).

Scenario 2: Capture the response of hydraulic head in absence of direct recharge.

Scenario 3: Reduction of serve abstraction by 50% through new strategies.

Scenario 4: Cover the growing demands through rising of pumping (50% more).

Scenario 5: Artificial groundwater recharge to recover the resultant drawdown in water levels.

Scenario 1: (No Intervention)

The groundwater model is predicted till 2035 in the case that there is no longer change either in abstraction or recharge. It can be seen from Figure 5-16 to Figure 5-17 that water level stays quite below simulated one sine original pumping was high and was reduced in calibration process.

Overall it can be noticed that the wells away from abstraction activates as in MTW-1 (Figure 5-17) has almost steady water table level which is in general greater than simulated one . This also can be referred to continuous groundwater recharge from the upstream.

Scenario 2: (No Direct Recharge)

The input source of recharge in terms of direct recharge from rainfall was neglected. This imposed seawater to intrude toward the study area with greater decline in heads. The intrusion risk appears clearly in coastal area where it has over extraction from the storage as IE and HTW-1 (Figure 5-16). The hydraulic heads drop to more than 6 and 11 m below sea level as seen in IE and HTW-1 respectively

Scenario 3: (Achieving safe yield through minimizing abstraction 50%)

Applying new strategies to lower high rates of extraction through encouraging farmers to replace traditional irrigation systems with automated techniques or initiating new policies for pumping control enable to balance the groundwater storage. This scenario predicts the future situation in case of reducing discharge up to 50%. From wells hydrograph (Figure 5-16) , it can be seen that there is

an increase in water levels in contrast to previous modeled durations. This guaranties a sustainable control to save groundwater from deterioration resulted from salt- water interface.

Scenario 4: (Allowing 50% more pumping to cover growing demands)

Growing seasonal crops in Al Suwayq area especially in summer implies more demands of water in addition to industrial and urban consumption. All of this resulted in more drawdown in water table levels. The impact of over abstraction up to 50% can be obviously observed in downstream areas as HTW-1 and IE (Figure 5-16). On the other hand, the observation wells in non-agricultural area as in MTW-1 are not affected by over consumption groundwater due to steady recharge from mountains.

Scenario 5: (Artificial Recharge)

This scenario requests injecting amounts of fresh water into the aquifer. The source of fresh water can be tertiary treated wastewater (TWW) or desalinated seawater. It was obtained that the average deficit of water resources in the concerned area is 335 Mm³ as accumulated volume from 2010 to 2017. To recover the happened deficit, a total of 51,000 m³/day (18.6 Mm³/year) is needed to be injected for the next eighteen years up to 2035. In this case eight recharge wells in different locations were installed with a daily rate of 6374 m³ to be injected artificially.

Wells hydrographs in figures below illustrate the role of future artificial recharge in recovering the decline in simulated heads. An increase in water levels reached to more than 4 m in wells having serve pumping as in HTW-1 is an evidence to indicate the role of injected treated wastewater to mitigate salinity.

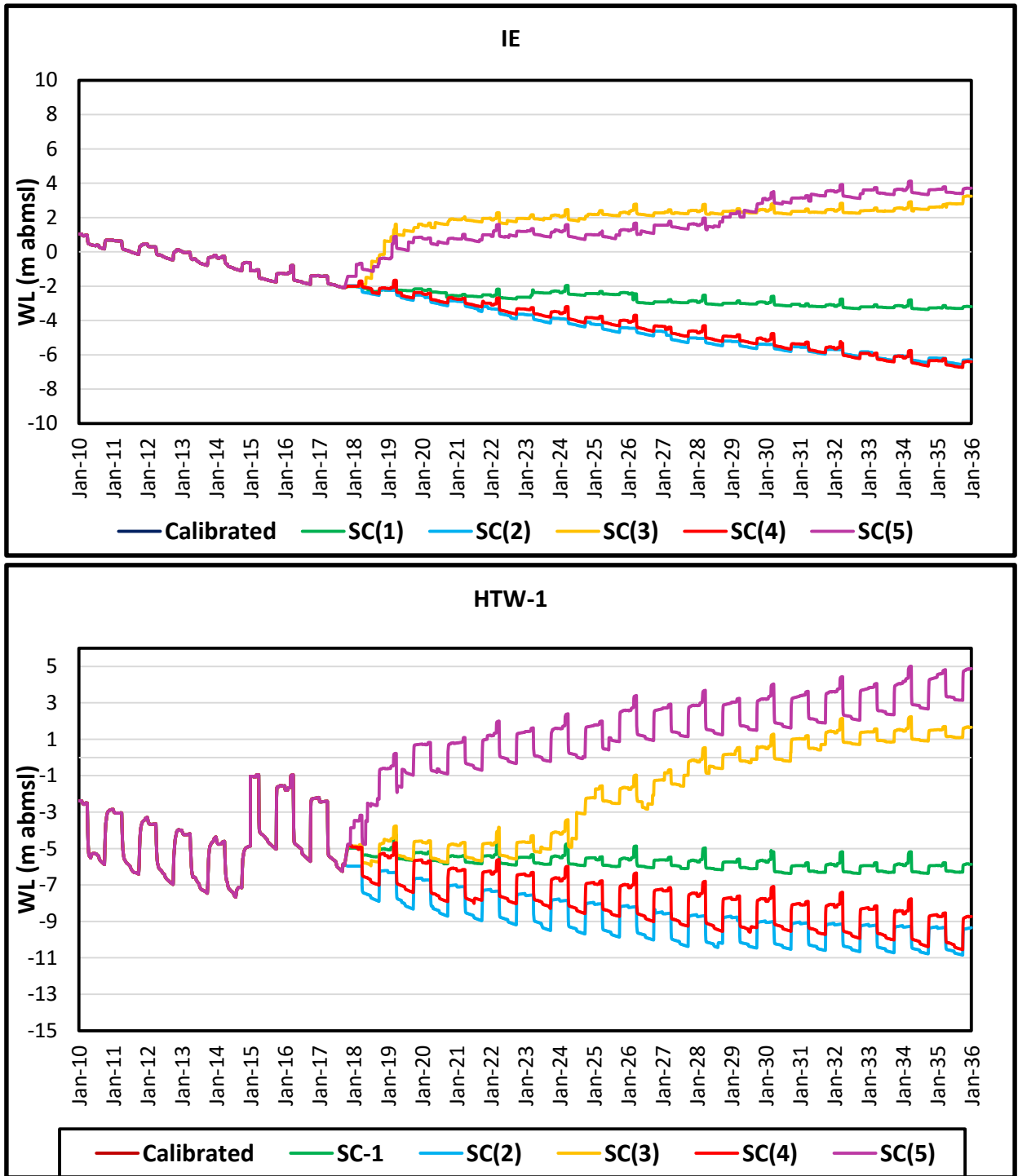


Figure 5-16: Predictive Scenarios in Coastal Area

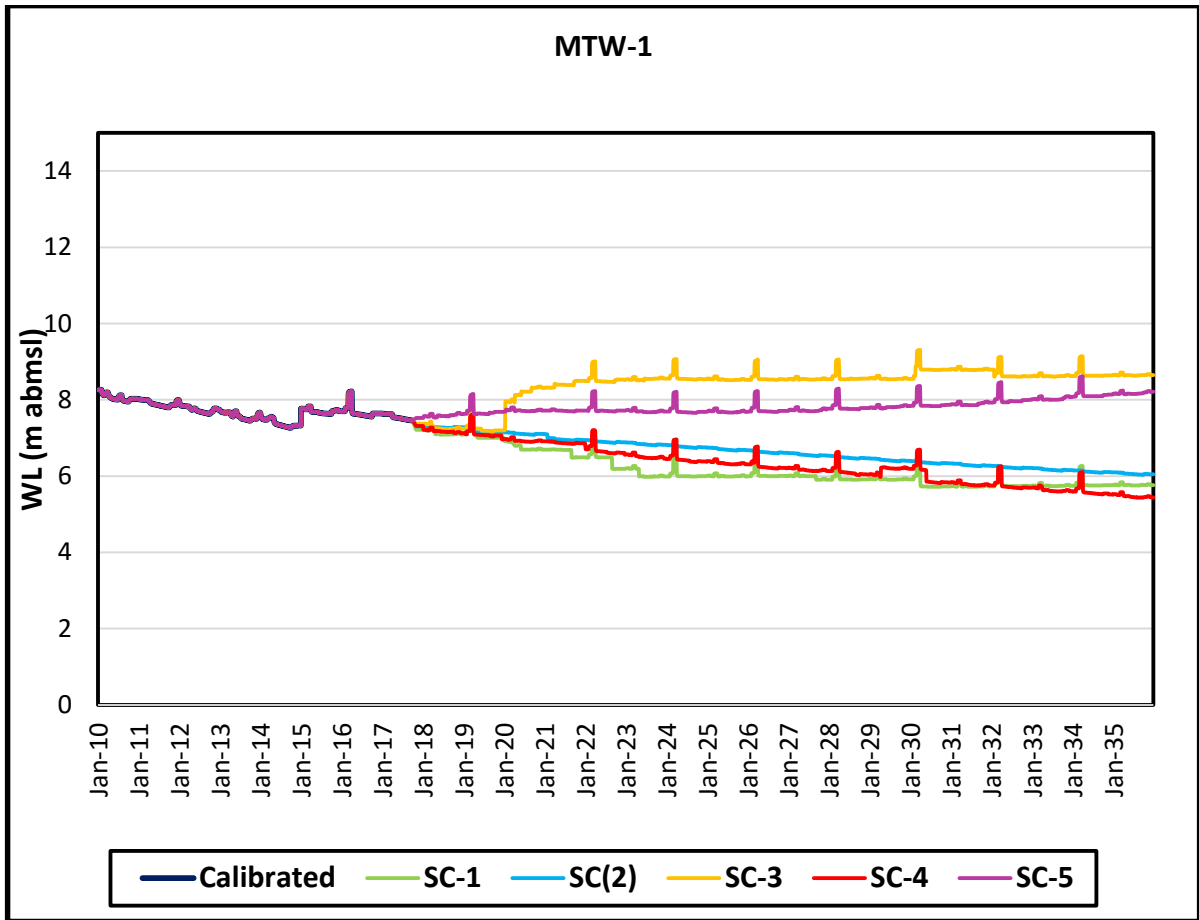


Figure 5-17: Predictive Scenarios in Upstream Area

Briefly, further predictive scenarios help to understand the long term effects of changes in hydrological system in duration of October 2017 to December 2035 to recommend the most proper management plan. It seems that the most proper management strategy is artificial recharge to lower the decrease in head. This is responsible for providing adequate and clean water to be extracted later on to meet higher consumption for irrigation, industrial and domestic uses. Also dams construction can introduce one efficient strategy to reduce the highest drawdown in water levels. However, injection of TWW or desalinated water remains the optimal one since the area receives small amount of rainfall and higher temperatures especially in summer days accelerate the evaporation.

Following to this, lowering pumping from aquifer is able enough to recover the existing decrease in water levels. This can be achieved through educating farmers to use modern automated irrigation systems and adopting them to grow economical crops irrigated by small amount of groundwater to come with optimal yield.

All of these strategies are considered as optimal solutions to resolve the risk of seawater intrusion and its negative impacts in providing healthy water for cropping system and to the soil. They are able to displace the saltwater and in turn the resulted salinity in agricultural lands.

Chapter 6

6. Conclusion and Recommendations

6.1 Conclusion

As Suwayq area represents wide agricultural area in Oman particularly in north Batinah coastal plain. It has big deficit in water resources from 1980's due to aggregated population in this plain, serve extraction from groundwater storage and scarcity of rainfall as located in arid climate. The declining of water table led to long term seawater intrusion which is keeping to advance more and more as a sequence of over pumping. All of these led to inverse impact to seasonal cropping process. For this, sustainability and efficient management plan need to be considered to tackle the recent phenomena of advancement of seawater inland.

Based on groundwater modeling using MODFLOW to evaluate the hydrological condition in As Suwayq area which locates in two important watershed catchments; Bani Ghafir and Mahya Mabrahw. Both catchments have the same geological units of alluvium underlined by upper fars aquifer. The model has an extent of 41 km in x direction and 17 km in y direction with a total area of 704 km². Boundary conditions, initial head, geology and hydrological parameters were considered in conceptualization process from available data from MRMWR and previously conducted researches.

Calibration of the model resulted in good fit between observed and simulated records with an interval of ± 2 m accuracy ($R^2=0.993$). It was obtained that groundwater inflow from highlands and abstraction from aquifer were the most sensitive parameters to be calibrated in both steady state and transient models. It was observed that the fluctuation in water level is affected by inflow recharge in upper boundary and extraction rate in downstream area. Likewise, hydraulic conductivity of alluvium layer played a role in calibration process in the entire aquifer within a range of 2.3 to 25 m/day in Mabrah catchment and 1.5 to 30 m/day in Ghafir catchment. Obviously, there is an increase in conductivity of alluvium

from west to east. Moving to upper fars, it has neglected role since no wells stay in this poorly porous strata. Similar to upper fars, dry climate with tiny amounts of rainfall in most of the days led to insignificant effect in storage of groundwater.

Calibrated model (2010-2017) concluded that there is an inverse flow from the sea intruding toward the interior boundary. Its impact significantly appears in coastal area as compared to upper boundary due to continuous recharge from Jabel. The abstraction overcomes total recharge from Jabel and rainfall about two times. The balance is compensated through release of water from unconfined storage and by seawater intrusion which lead to salinity. This is indicated through the long term gradual decrease in water head from well hydrographs and this decline is steeper in coastal wells as to upper ones.

To recover the drawdown obtained from high withdrawal from the aquifer, managed aquifer recharge (MAR) in sense of artificial injection introduces an optimal solution to shift the intrusion backward. Accordingly, 51,000 m³/day of tertiary TWW or desalinated water is adequately sufficient to reclaim seawater intrusion. This fresh water is almost able to purify the saline water. Furthermore, educating farmers about culture of saving water as national wealth. This is interrupted through making people aware about the efficiency of modern automated irrigation systems which can save water and effort. Beside to these, growing effective crops that yields more with less water is one optimistic solution to improve water quality. These will contribute to lower pumping rates to get the desired water balance.

6.2 Model Limitations

Groundwater model is an approximate representation of actual aquifer system (Anderson et al., 1992). In any model, the efficiency of it is usually associated with clear formulating of model purposes, necessary data to present the quantity and quality of groundwater, deep understanding of the aquifer, and further assumption for model development (Amerjeed, 2016). A missing or absence in one of listed factors generates limitations to the model in term of uncertainty.

As mentioned above that the success of any groundwater model implies the availability of all related parameters in term of geological and hydrological parameters and boundary conditions. However limitation of insufficient data belonged to layers elevation is one challenge that create uncertainty of the final model. In this study, small number of boreholes have top and bottom elevations of both layers and however most of these elevations were inaccurate especially ground surface elevation that was checked through Google Earth. In addition to this, lack of geological data as hydraulic conductivity, specific storage and specific yield as mentioned in chapter 3. Normally, these data are derived from different pumping test initiated in scattered locations. In contrast to this and because these investigations are not close from each other, heterogeneity of aquifer can not be addressed correctly. All of these impact the certainty of the model that needs to be calibrated later on.

Furthermore, there was no date to show the real pumping in area of the study. There was no more data than inventory wells data from 1992 to be considered for modeling purposes. The rate was given as an average per day not the real one. Usually the abstraction varies from day to day and from season to season such as water demand in summer overcomes the rate in winter due to high evaporation in hot temperatures. Also, the demand varies based on the type of usage of abstracted water.

The main limitation challenge that was brought to this model was water levels data. There was a range of inaccuracy while measuring the level of water. Also, some wells still are operated but they have no measured date in some years. All of these issues were sorted through excluding of uncertain reading.

6.3 Recommendations

Satisfied degree of confidence is established through the gained results and good matching between estimated and actual data after calibration step. Still the gap among the data is incorporated due to uncertainty level of available data.

Modeling will remain as the significant tool for post –audi activities in the area of study that are highly recommended for further adjustment or improvement. It can be considered as elementary model that shall be improved to get more powerful precise model that can be base for other researches. These recommendation will be briefly summarized as follow:

- Enhancing research projects to support groundwater studies in the region and related quantity and quality. Beside to this artificial recharge should be given a priority in process of research.
- More field observations need to be organised to clarify aquifer system accurately and delineate hydrological and geological parameters such as hydraulic conductivity, porosity, specific yield and specific storage.
- Water level, abstraction and recharge data have to be monitored closely to establish reliable data base that would be beneficial for further studies. Also, they will trust individuals and organization for conducting more researches in groundwater study. Extraction rate should be observes in timely basis with concerning about all types of consumptions such as domestic, industrial and agricultural.
- Public awareness and incentives to people against highly abstraction through educating them that the water has to be given an amendatory value as it is a national wealth. This is achieved through encouraging farmers to use advanced irrigation methods and cultivation of plants that require less water with optimal yield.
- Issuing new legislations with polices of charges and punishments by MAF and MRMWR. These polices include usage of water resources, land use and drilling of wells.

- Groundwater development projects need to be implemented to ensure the balance between input and output flows to ensure the sustainability of water resources and prevent seawater intrusion.
- Evaluate the feasibility of MAR through dams construction and injection of tertiary treated wastewater (TWW) or desalinated water into aquifer to balance the obtained decrease in water levels.
- Environmental impact assessment (EIA) shall be involved in managed aquifer recharge or artificial recharge to monitor the quality or health of injected water which have to meet health standards.

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Appendixes

Appendix A: Boreholes Data

ID	x	y	Z	Material
NB-17	527015.3	2634449	42	1
NB-17	527015.3	2634449	0	2
NB-17	527015.3	2634449	-561	2
NB-18	528416.5	2637063	23	1
NB-18	528416.5	2637063	-24	2
NB-18	528416.5	2637063	-627	2
NB-19	524617.3	2630040	74	1
NB-19	524617.3	2630040	42	2
NB-19	524617.3	2630040	-226	2
NB-20	547504	2627757	27	1
NB-20	547504	2627757	-23	2
NB-20	547504	2627757	-614	2
NB-21	547196.1	2622615	51	1
NB-21	547196.1	2622615	15	2
NB-21	547196.1	2622615	-579	2
NB-21T	547179	2622591	51	1
NB-21T	547179	2622591	15	2
NB-21T	547179	2622591	-109	2
NB-22	537485.3	2620715	87	1
NB-22	537485.3	2620715	71	2
NB-22	537485.3	2620715	-229	2
JT_10	537200	2615700	129	1
JT_10	537200	2615700	80	2
JT_10	537200	2615700	52.7	2
NC_9	558290	2627010	10	1
NC_9	558290	2627010	-90	1
MAB-2	527789.4	2632864	51	1
MAB-2	527789.4	2632864	31	1
NC_10	552450	2631000	8	1
NC_10	552450	2631000	-93	2
NC_10	552450	2631000	-98	2
MAB-5	524986	2632847	57	1
MAB-5	524986	2632847	37	1
ADW-19	539000	2630000	30	1

ADW-19	539000	2630000	-10	1
ADG-26	548800	2632000	16	1
ADG-26	548800	2632000	-29.7	1
MAB-4	526083	2633909	47	1
MAB-4	526083	2633909	17	1
JT-20A	536948	2615822	127	1
JT-20A	536948	2615822	75	1
JT-22	537300	2622100	60	1
JT-22	537300	2622100	-82	1
BG-2	546400	2614300	24	1
BG-2	546400	2614300	-67	1
ADG-25	543600	2633800	15	1
ADG-25	543600	2633800	-20.7	1
JT-20	536832	2615822	130	1
JT-20	536832	2615822	-11	1
BMET	557500	2624700	11	1
BMET	557500	2624700	-13	1
BG-1	551200	2625700	26	1
BG-1	551200	2625700	-27	1

***1 and 2 refer to Alluvium and Upper Fars aquifer respectively**

Appendix B: Layers Elevation Data

Name	X	Y	Distance from Sea (km)	Top of Alluvium (m)	Bottom of Alluvium (m)	Bottom of UF	Thickness of Alluvium	Thickness of UF
P1	524285.4	2636797	7.4	35	-30	-588	65	558
P2	524282.5	2639145	5.1	25	-40	-593	65	553
P5	546569.7	2615168	19.2	135	70	-315	65	385
P19	544273.4	2628407	10.0	29	-23	-577	52	554
P26	544276	2628638	9.3	36	-25	-582	61	557
P28	516061.5	2631590	15.0	88	-15	-545	103	530
P41	521650	2645330	0.4	7	-40	-600	47	560
P43	524970	2643950	0.4	8	-40	-600	48	560
P46	528782.2	2632286	10.6	49	-23	-577	72	554
P47	532170	2639910	1.8	6	-42	-598	48	556
P49	539810	2638020	1.3	8	-42	-598	50	556
P51	533580	2636630	4.6	16	-40	-595	56	555
P57	524900	2643330	0.9	11	-42	-600	53	558
P59	526580	2640710	2.9	14	-40	-596	54	556
P61	534420	2638410	1.6	6	-40	-600	46	560
P66	539940	2638850	0.4	5	-40	-600	45	560
P68	557649.9	2627776	4.9	12	-40	-595	52	555
P70	532430	2641030	0.6	1	-42	-600	43	558
P74	521050	2645250	0.6	7	-43	-600	50	557
P75	521310	2642880	2.6	13	-40	-598	53	558
P77	524450	2644120	0.3	5	-41	-600	46	559
P80	529280	2640720	1.9	9	-42	-598	51	556
P81	529570	2640380	2.2	9	-40	-598	49	558
P82	529860	2641460	1.0	2	-44	-600	46	556
P85	533040	2637440	3.9	12	-40	-597	52	557
P87	538420	2639130	0.5	6	-43	-600	49	557
P92	518620	2644990	1.9	11	-42	-598	53	556
P96	529620	2641500	1.0	7	-44	-600	51	556
P104	522110	2642370	2.8	15	-40	-596	55	556
P105	524330	2643570	0.9	10	-42	-600	52	558
P107	523280	2642810	2.0	11	-40	-598	51	558
P108	523720	2644460	0.3	5	-41	-600	46	559

P111	532410	2639230	2.5	7	-40	-598	47	558
P122	526920	2642620	0.9	8	-42	-600	50	558
P123	522210	2643050	2.1	11	-40	-598	51	558
P124	522630	2644880	0.4	7	-40	-600	47	560
P125	526290	2643570	0.2	6	-43	-600	49	557
P126	529520	2641320	1.2	7	-42	-598	49	556
P133	536100	2637000	3.5	10	-40	-597	50	557
P136	520120	2645950	0.3	7	-43	-600	50	557
P137	520820	2644610	1.3	9	-42	-598	51	556
P138	522480	2644430	0.7	6	-42	-600	48	558
P139	524120	2642690	1.9	10	-42	-598	52	556
P140	525080	2642220	2.0	13	-40	-598	53	558
P153	522010	2644500	0.9	7	-42	-600	49	558
P156	524870	2643840	0.5	8	-43	-600	51	557
P161	533610	2640300	1.1	1	-44	-600	45	556
A2	530730	2640410	1.8	5	-42	-598	47	556
A3	528026	2643026	0.1	2	-45	-600	47	555
A41	533950	2638868	2.3	9	-40	-598	49	558
A43	534910	2638900	1.9	6	-42	-598	48	556
A48	534732	2638360	2.5	6	-40	-598	46	558
A58	535420	2638280	2.3	7	-40	-598	47	558
A60	535560	2638646	1.9	6	-42	-598	48	556
A62	534624	2638393	2.7	8	-40	-598	48	558
A64	534030	2639090	2.0	4	-40	-598	44	558
A71	534640	2637410	3.4	12	-40	-597	52	557
A74	534297	2636066	4.8	15	-40	-595	55	555
A75	534175	2635609	5.3	16	-40	-593	56	553
A77	535917	2636102	4.4	16	-40	-595	56	555
A80	533935	2634964	5.9	20	-40	-593	60	553
A96	536326	2638206	2.2	10	-40	-598	50	558
A117	537300	2638368	1.7	8	-42	-598	50	556
A118	537064	2637482	2.5	7	-40	-598	47	558
A125	539118	2638336	1.1	7	-44	-600	51	556
A127	538253	2638659	1.0	10	-44	-600	54	556
A133	538169	2638235	1.5	8	-42	-598	50	556
A138	533453	2632826	8.2	32	-28	-585	60	557
A139	536519	2631847	8.6	30	-28	-585	58	557
A141	538312	2631476	8.0	29	-28	-585	57	557
A146	528186	2642089	1.0	7	-44	-600	51	556
A157	528697	2642562	0.4	5	-40	-600	45	560

A160	528738	2642149	0.7	4	-42	-600	46	558
A167	535830	2639783	0.8	3	-42	-600	45	558
A169	535748	2639550	1.0	4	-44	-600	48	556
A180	535706	2639098	1.5	4	-42	-598	46	556
A206	539038	2637709	1.7	9	-42	-598	51	556
A215	532224	2640352	1.3	6	-42	-598	48	556
A234	536601	2639383	0.9	6	-42	-600	48	558
A245	536820	2639765	0.5	5	-43	-600	48	557
A273	536522	2638903	1.4	6	-42	-598	48	556
A274	540552	2638441	0.7	7	-42	-600	49	558
A276	541195	2638384	0.6	5	-42	-600	47	558
A277	540999	2637239	1.8	10	-42	-598	52	556
A282	540343	2637861	1.4	10	-42	-598	52	556
A294	541042	2637597	1.4	11	-42	-598	53	556
A297	541118	2638102	0.9	6	-42	-600	48	558
A299	541123	2637949	1.0	6	-44	-600	50	556
A308	526576	2640770	2.7	13	-40	-598	53	558
A317	537494	2638930	1.0	6	-44	-600	50	556
A319	537508	2639425	0.6	6	-42	-600	48	558
A333	537887	2638432	1.4	7	-42	-598	49	556
A337	537455	2639221	6.1	5	-36	-588	41	552
A347	538598	2635948	3.6	17	-40	-597	57	557
A357	537694	2636529	3.6	12	-40	-597	52	557
A362	538339	2635150	4.6	16	-40	-595	56	555
A366	538250	2634458	5.3	21	-40	-593	61	553
A373	537343	2634730	5.2	20	-40	-593	60	553
A376	536834	2633055	7.0	26	-30	-588	56	558
A385	541516	2637996	0.9	7	-42	-600	49	558
A391	541565	2637546	1.4	11	-42	-598	53	556
A400	538783	2637091	2.5	9	-40	-598	49	558
A409	537932	2638159	1.6	8	-40	-600	48	560
A416	530822	2641300	0.8	3	-42	-600	45	558
A419	530924	2641610	0.5	3	-43	-600	46	557
A439	531198	2638923	3.0	14	-40	-597	54	557
A442	531120	2638500	3.4	16	-40	-597	56	557
A445	531289	2639235	2.7	11	-40	-598	51	558
A468	530851	2639234	2.9	12	-40	-598	52	558
A470	530704	2638933	3.7	12	-40	-597	52	557
A473	531015	2637640	4.3	18	-40	-595	58	555
A477	530510	2638079	4.5	17	-40	-595	57	555

A478	530172	2637926	3.9	18	-40	-597	58	557
A481	530945	2639704	2.4	7	-40	-598	47	558
A487	530201	2638484	3.9	14	-40	-597	54	557
A492	529290	2637468	5.2	20	-40	-593	60	553
A493	529968	2637533	4.8	18	-40	-595	58	555
A497	530363	2638970	3.4	14	-40	-597	54	557
A505	534356	2640446	0.7	2	-42	-600	44	558
A510	534352	2640326	0.8	2	-42	-600	44	558
A513	534258	2639685	1.5	3	-42	-598	45	556
A520	540089	2636701	2.6	11	-40	-598	51	558
A526	540273	2637013	2.2	10	-40	-598	50	558
A543	540590	2635869	3.3	10	-40	-597	50	557
A548	541184	2636253	2.7	8	-40	-598	48	558
A549	541029	2635883	3.1	12	-40	-597	52	557
A550	540817	2636482	2.6	9	-40	-598	49	558
A552	539495	2636849	2.5	12	-40	-598	52	558
A553	527878	2642725	0.5	9	-43	-600	52	557
A563	539989	2635764	3.5	16	-40	-597	56	557
A571	540523	2635493	3.6	10	-40	-597	50	557
A577	539313	2635845	3.6	11	-40	-597	51	557
A587	539077	2635325	4.1	14	-40	-595	54	555
A588	538996	2634922	4.8	18	-40	-595	58	555
A591	538831	2634117	5.3	21	-40	-593	61	553
A597	539644	2634803	4.6	15	-40	-595	55	555
A599	539851	2635115	4.1	12	-40	-595	52	555
A603	538733	2633878	5.6	23	-40	-593	63	553
A605	538224	2633772	5.9	23	-40	-593	63	553
A609	538782	2633339	6.2	23	-36	-588	59	552
R3	553563.1	2634737	0.5	4	-43	-600	47	557
R4	556223.1	2632143	1.3	1	-42	-598	43	556
R9	557741.1	2630739	2.2	4	-40	-598	44	558
R10	556427	2631867	1.6	2	-40	-600	42	560
R13	552259	2634515	0.7	2	-42	-600	44	558
R18	543921	2637477	0.7	6	-42	-600	48	558
R20	556537	2630577	2.7	5	-40	-598	45	558
R22	551895	2633351	2.2	2	-40	-598	42	558
R24	525475	2644045	0.0	1	-45	-600	46	555
R25	551639	2635393	0.1	4	-45	-600	49	555
R28	539137	2638051	1.4	6	-42	-598	48	556
R38	519909	2646317	0.1	6	-45	-600	51	555

R40	558099	2627263	5.2	12	-40	-593	52	553
R47	528427	2642841	0.1	6	-45	-600	51	555
R49	523189	2644797	0.1	5	-45	-600	50	555
R55	550500.9	2632195	3.6	11	-40	-597	51	557
R56	548742.9	2633393	3.5	12	-40	-597	52	557
R57	541942.9	2636673	2.2	9	-40	-598	49	558
R62	557252.9	2625851	7.1	13	-30	-588	43	558
R63	518778.9	2644193	2.4	10	-40	-598	50	558
R65	545034.9	2634679	3.0	12	-40	-597	52	557
R74	555122.8	2627485	6.4	15	-36	-588	51	552
R77	552460.9	2629299	5.6	13	-40	-593	53	553
R80	541598.9	2634231	4.9	14	-40	-595	54	555
R84	528180.9	2639793	3.0	17	-40	-597	57	557
R90	552129	2628089	6.9	16	-36	-588	52	552
R91	519676.8	2642521	3.7	17	-40	-597	57	557
R92	532750.9	2636683	4.8	17	-40	-595	57	555
R95	548114.7	2630567	6.0	17	-36	-588	53	552
R101	532544.8	2635865	5.6	22	-40	-593	62	553
R104	550058.8	2627675	8.0	20	-28	-585	48	557
R106	547657	2629195	8.0	20	-28	-585	48	557
R107	527264.8	2637717	1.9	22	-42	-598	64	556
R110	545808.7	2629935	8.1	26	-28	-585	54	557
R111	542658.8	2631703	6.5	23	-36	-588	59	552
R115	517672.8	2640969	6.0	26	-36	-588	62	552
R116	520542.8	2639817	5.7	27	-40	-593	67	553
R117	547942.8	2628211	8.5	24	-28	-585	52	557
R118	530144.7	2635955	6.7	29	-36	-588	65	552
R119	518880.8	2640485	5.8	27	-40	-593	67	553
R121	538890.8	2631125	8.6	30	-28	-585	58	557
R122	552192.8	2623799	10.8	32	-23	-577	55	554
R123	531350.8	2634763	7.7	33	-30	-588	63	558
R124	545544.8	2628641	9.0	31	-25	-582	56	557
R126	549114.8	2626639	10.1	30	-23	-577	53	554
R129	556314.8	2621507	11.5	34	-22	-575	56	553
R130	524838.8	2637103	6.7	30	-36	-588	66	552
R131	534800.8	2631861	9.6	35	-25	-582	60	557
R132	520424.8	2638763	6.8	31	-36	-588	67	552
R133	543586.8	2628105	10.9	36	-23	-577	59	554
R136	522166.8	2637707	7.1	35	-30	-588	65	558
R146	548502.8	2623445	12.3	43	-22	-570	65	548

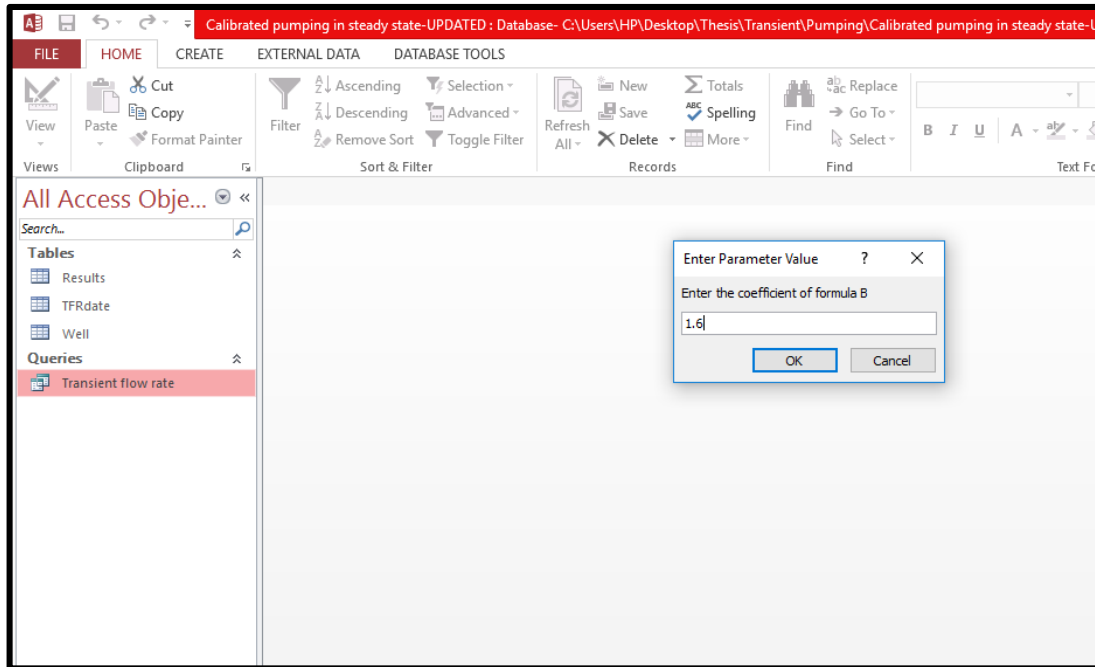
R147	519586.8	2636985	9.0	44	-25	-582	69	557
R148	522030.8	2636409	9.0	41	-25	-582	66	557
R152	528950.8	2632905	9.6	48	-25	-582	73	557
R157	534788.9	2627977	12.3	53	-22	-570	75	548
R162	526612.8	2632861	10.3	51	-23	-577	74	554
R164	523972.7	2633711	10.3	53	-23	-577	76	554
R165	544258.8	2623617	16.4	57	-5	-524	62	519
R171	539246.8	2624853	14.6	61	-18	-563	79	545
R174	551246.8	2619179	15.9	66	-15	-545	81	530
R177	520610.8	2633063	12.8	68	-22	-570	90	548
R182	532534.8	2625281	18.2	74	20	-410	54	430
R184	538864.8	2621867	18.5	81	20	-410	61	430
R187	550932.8	2616945	17.4	84	10	-480	74	490
R189	514714.8	2633591	13.9	86	-20	-568	106	548
R191	514634.8	2632789	14.8	84	-18	-563	102	545
R192	522548.8	2629125	15.1	89	-15	-545	104	530

*Top of Alluvium was estimated using Google Earth

**Bottom of Alluvium and Upper Fars were obtained from Bani Ghafir cross section.

Appendix C: Calculating Transient Pumping Using Microsoft Access

Step1: Entering coefficients based on pumping seasonal changes



Step2: Getting the results in different stresses periods

The screenshot shows the Microsoft Access interface with the 'Transient flow rate' table open. The table has the following columns: Well, X, Y, Date, and Discharge Q. The data is organized by year and date, showing discharge rates for multiple wells over time.

Well	X	Y	Date	Discharge Q
Well 4-1	530730.0	2640410.0	1/1/2015	-5.143
Well 4-1	530730.0	2640410.0	4/1/2015	-5.143
Well 4-1	530730.0	2640410.0	4/1/2015	-20.570
Well 4-1	530730.0	2640410.0	7/1/2015	-20.570
Well 4-1	530730.0	2640410.0	7/1/2015	-21.856
Well 4-1	530730.0	2640410.0	10/1/2015	-21.856
Well 4-1	530730.0	2640410.0	10/1/2015	-3.857
Well 4-1	530730.0	2640410.0	1/1/2016	-3.857
Well 4-1	530730.0	2640410.0	1/1/2016	-5.143
Well 4-1	530730.0	2640410.0	4/1/2016	-5.143
Well 4-1	530730.0	2640410.0	4/1/2016	-20.570
Well 4-1	530730.0	2640410.0	7/1/2016	-20.570
Well 4-1	530730.0	2640410.0	7/1/2016	-21.856
Well 4-1	530730.0	2640410.0	10/1/2016	-21.856
Well 4-1	530730.0	2640410.0	10/1/2016	-3.857
Well 4-1	530730.0	2640410.0	1/1/2017	-3.857
Well 4-1	530730.0	2640410.0	1/1/2017	-5.143
Well 4-1	530730.0	2640410.0	4/1/2017	-5.143
Well 4-1	530730.0	2640410.0	4/1/2017	-20.570
Well 4-1	530730.0	2640410.0	7/1/2017	-20.570
Well 4-1	530730.0	2640410.0	7/1/2017	-21.856
Well 4-1	530730.0	2640410.0	10/1/2017	-21.856
Well 4-1	530730.0	2640410.0	10/1/2017	-3.857
Well 4-2	528026.0	2643026.0	1/1/2015	-12.856
Well 4-2	528026.0	2643026.0	4/1/2015	-12.856

Step3: Double check that in each year the total pumping in all stresses periods in that year is equal to the pumping rate for that well in that year ($Q \times 365 \text{ days}$)

Calibrated pumping in steady state-UPDATED - Database- C:\Users\HP\Desktop\Calibrated pumping in steady state-UPDATED.accdb (A)

FILE HOME CREATE EXTERNAL DATA DATABASE TOOLS

View Paste Copy Cut Copy Paste Format Painter Filter Sort & Filter

Ascending Descending Remove Sort Selection Advanced Toggle Filter Refresh All New Save Delete Records

Totals Spelling More Find Go To Select Calibri B I U

All Access Obj... << Transient flow rate Compare

Search... Tables Results TFRdate Well Queries Compare Transient flow rate

Well	Discharge Q	Q*365	A*90+B*91+C*92+D*92
Well 4-1	-12.856	-4692.5568	-4700.270592
Well 4-2	-32.141	-11731.392	-11750.67648
Well 4-6	-246.413	-89940.672	-90088.51968
Well 4-14	-332.122	-121224.384	-121423.65696
Well 4-22	-324.086	-118291.536	-118485.98784
Well 4-23	-350.870	-128067.696	-128278.21824
Well 4-48	-184.810	-67455.504	-67566.38976
Well 4-49	-369.619	-134911.008	-135132.77952
Well 4-65	-289.267	-105582.528	-105756.08832
Well 4-66	-137.938	-50347.224	-50429.98656
Well 4-67	-166.061	-60612.192	-60711.82848
Well 4-68	-187.488	-68433.12	-68545.6128
Well 4-69	-203.558	-74298.816	-74420.95104
Well 4-70	-110.709	-40408.779744	-40475.20513536
Well 4-71	-203.558	-74298.816	-74420.95104
Well 4-73	-391.046	-142731.936	-142966.56384
Well 4-74	-184.810	-67455.504	-67566.38976
Well 4-75	-412.474	-150552.864	-150800.34816
Well 4-76	-246.413	-89940.672	-90088.51968
Well 4-77	-203.558	-74298.816	-74420.95104
Well 4-78	-166.061	-60612.192	-60711.82848
Well 4-79	-203.558	-74298.816	-74420.95104
Well 4-80	-166.061	-60612.192	-60711.82848
Well 4-81	-203.558	-74298.816	-74420.95104
Well 4-82	-166.061	-60612.192	-60711.82848

Record: 1 No Filter Search