4-2017

Modeling the Mitigation of Seawater Intrusion By Pumping Brackish Water from the Coastal Aquifer Of Wadi Ham, UAE

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MODELING THE MITIGATION OF SEAWATER INTRUSION BY PUMPING BRACKISH WATER FROM THE COASTAL AQUIFER OF WADI HAM, UAE

Modou A. Sowe

This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Water Resources

Under the Supervision of Dr. Mohamad Mostafa Ahmed Mohamed

April 2017

Declaration of Original Work

I, Modou A. Sowe, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Modeling the Mitigation of Seawater Intrusion by Pumping Brackish Water from the Coastal Aquifer of Wadi Ham, UAE*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Dr. Mohamad Mostafa Ahmed Mohamed, in the College of Engineering at UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

The control and management of seawater intrusion in coastal aquifers is a major challenge in the field of water resources management. Seawater intrusion is a major problem in the coastal aquifer of Wadi Ham, United Arab Emirates caused by intensive groundwater abstraction from increased agricultural activities. This has caused the abonnement of salinized wells and ultimately affected farming activities and domestic water supply in the area. In this study, the 3D finite element groundwater flow and solute transport model, FEFLOW was used to simulate pumping of brackish water from the intrusion zone to control seawater intrusion in the aquifer. The model was calibrated and validated with available records of groundwater levels and salinity distribution. Different simulation scenarios were conducted to obtain optimum pumping locations, rates as well as number of wells. It was found that pumping at a distance of 1500 m from the shoreline at 500m^3/day using 16 installed wells is the optimum simulation. A comparison between scenarios of non-pumping and pumping was conducted. Results showed an increased in salt concentration in groundwater under the non-pumping scenario while it decreased under the pumping scenario. Under non-pumping scenario isoline 35,000 mg/l was observed to have intruded into the eastern southern part of the aquifer while maximum isoline observed for the same area under pumping scenario was 20,000 mg/l. This result showed an overall improvement in salt concentration in groundwater distribution and ultimately halted seawater intrusion in the aquifer.

Keywords: Coastal aquifer, groundwater management, numerical modeling, pumping brackish water, seawater intrusion.

Title and Abstract (in Arabic)

نمذجة التخفيف من تداخل مياه البحر عن طريق ضخ المياه المالحة من الحوض الساحلي في وادي حام، دولة الإمارات العربية المتحدة

الملخص

إن مراقبة وإدارة تسرب مياه البحر الجوفية الساحلية تشكل تحديا كبيرا في مجال إدارة الموارد المائية. يشكل تسرب مياه البحر مشكلة رئيسية في المياه الجوفية الساحلية في وادي حام في إمارة الفجيرة (الإمارات العربية المتحدة) نتيجة استخراج المياه الجوفية المكثفة الناتج عن زيادة الأنشطة الزراعية، تجري الدراسة الحالية للسيطرة على تسرب مياه البحر عن طريق تركيب آبار ضخ إضافية في منطقة الدراسة. وضعت هذه الدراسة حالة مستقرة، نموذج التدفق ونموذج النقل المذاب باستخدام برنامج المياه الجوفية فيفلو. يعاد شحن طبقة المياه الجوفية في منطقة الدراسة بسبب هطول الأمطار، وثلاثة من الأودية تقع باتجاه الجنوب والشمال والغرب. تم معايرة النموذج باستخدام السجلات المتوفرة لجدول المياه الجوفية والملوحة. لقد تم تطوير ثلاثة سيناريوهات مختلفة لتقييم تأثير الضخ على نموذج التدفق. ثم، محاكاة ضخ المياه المالحة في منطقة التسرب لتقييم آثاره في السيطرة على تسرب مياه البحر. أظهرت نتائج السيناريو المحاكي بنسبة 5٪ زيادة في الضخ انخفاضا متزايدا في مستوى المياه الجوفية في حين أن سيناريو انخفاض الضخ بنسبة 5٪ كان له تأثير ضئيل على مستوى المياه الجوفية. أظهرت محاكاة نتائج سيناريو المياه الملوحة انخفاض في توزيع تركيز الملوحة في المياه الجوفية. إن مواقع الضخ المثلى ومعدل الضخ وعدد الآبار وجدت على مسافة 1500 متر من الشاطئ بمعدل 600 متر مكعب لليوم الواحد للبئر لـ15 بئر مثبت على التوالي. أظهر سيناريو المقارنة ما بين عدم ضخ المياه وضخها زيادة وانخفاض في نسبة الملوحة في المياه الجوفية في إطار السيناريوهات ذات الصلة. في ظل سيناريو عدم الضخ، لوحظ أن إيزولين 35000 ملغم / لتر قد تدخل في الجزء الجنوبي الشرقي من طبقة المياه الجوفية، بينما كان الحد الأقصى الذي رصده إيزولين لنفس المنطقة تحت سيناريو الضخ 20000 ملغم / لتر. وباختصار، لوحظ تحسن عام في نوعية المياه الجوفية في منطقة الدراسة.

مفاهيم البحث الرئيسية: النمذجة العددية؛ التخفيف من تسرب مياه البحر، المياه الجوفية الساحلية، وادي هام، التسلل في المياه المالحة، تدبير التخفيف، فيفلو.

Acknowledgements

I would like to thank God for giving me the faith and strength to successfully complete my research. My profound gratitude and thanks goes to my supervisor Dr. Mohamad Mostafa Ahmed Mohamed whose advice and support helped me to get through my studies with ease. I am especially grateful to Prof. Mohsen Sherif for acting as a co-advisor to my thesis work and whose in-depth research findings formed a cornerstone of my thesis research project.

I would like to thank my committee for their guidance, support, and assistance throughout my preparation of this thesis. I would like to thank Prof. Walid Elshaobagy who was very helpful during my enrollment as a student in the Water Resources Graduate Program and for recommending me to be hired as a Graduate Teaching Assistance. My special thanks goes to research associate Dr. Sathish Sadhasivam for being extremely helpful with assisting me in learning how to use the FEFLOW model. I would also like to acknowledge and thank Mrs. Shrieen Wolied a Digital Technician at Libraries Deanship UAEU for her help in printouts. We would like to thank and acknowledge DHI-WASY GmbH group Dubai office for giving us a free license to use the FEFLOW model. Special thanks to all faculty members in the Department of Civil and Environmental Engineering and to the United Arab Emirates University for assisting me throughout my studies and research.

And finally, special thanks goes to my mother, wife, and family whose understanding and patience helped me along the way.

Dedication

To my beloved mother, wife and family

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List of Abbreviations

EC	Electronic Conductivity
FAO	Food and Agricultural Origination
GCC	Gulf Council Cooperation
IPCC	Intergovernmental Panel on Climate Change
MCM	Million Cubic Meters
MSL	Mean Sea Level
NCMS	National Center of Meteorological and Seismology
PPM	Parts per million
SWI	Seawater Intrusion
TDS	Total Dissolved Solids
UAEU	United Arab Emirates University
USGS	United States Geological Survey

Chapter 1: Introduction

1.1 Water Distribution on Earth

Water is the basic element of life for all living things on Earth. The earth's water resources are core to development and continues existence of living and non-living things on earth. This makes water; the most precious resources on earth yet its importance is for the most part overlooked. The available freshwater on earth is just about 2.5% of the total available water on earth with most of this freshwater frozen in glaciers and ice sheets. And about 96% of all liquid freshwater can be found underground with surface water holding about 0.3% of the total freshwater. The global population has increased from 6 to 7 billion in just over a decade and the rate of growth is steadily increasing. World population is projected to grow from 6.1 billion in 2000 to 8.9 billion in 2050, increasing therefore by 475% (UN World Population to 2300, 2004). The effects and impacts of climate change on the earth surface is one of the major threats to human existence. These are factors that are directly linked to the sustainability of life on earth. As the population that depends on freshwater resources are increasing, so as the effects, impacts and uncertainties of climate change couple with increase anthropogenic activities that affects freshwater resources. This makes the issue of water resources management very critical in our today's world as it is the key to the sustainability of life on earth (CLP Mag, 2011).

The world population is unevenly distributed so as the available freshwater resources, although the world population is increasing as whole; there are countries or regions that are experiencing decline in their populations. It is interesting to note that the regions with the higher population growth are subjected to some level of freshwater challenges. Projections have shown that 90% of the African continent would experience economic water scarcity by 2025 with the remaining 10% experiencing physical water scarcity (WWAP, 2012) as highlighted in Figure 1. The whole of the Middle Eastern countries are at least expected to experience physical water scarcity and greater parts of China and India with Australia and South America experiencing economic water scarcity. These regions represent the greater chunk of the global population as well as higher population growth and as such the issue of water resources management requires utmost attention. Water resources are being altered due to changes in climate, population, economic development and environmental considerations (IPCC, 2008).

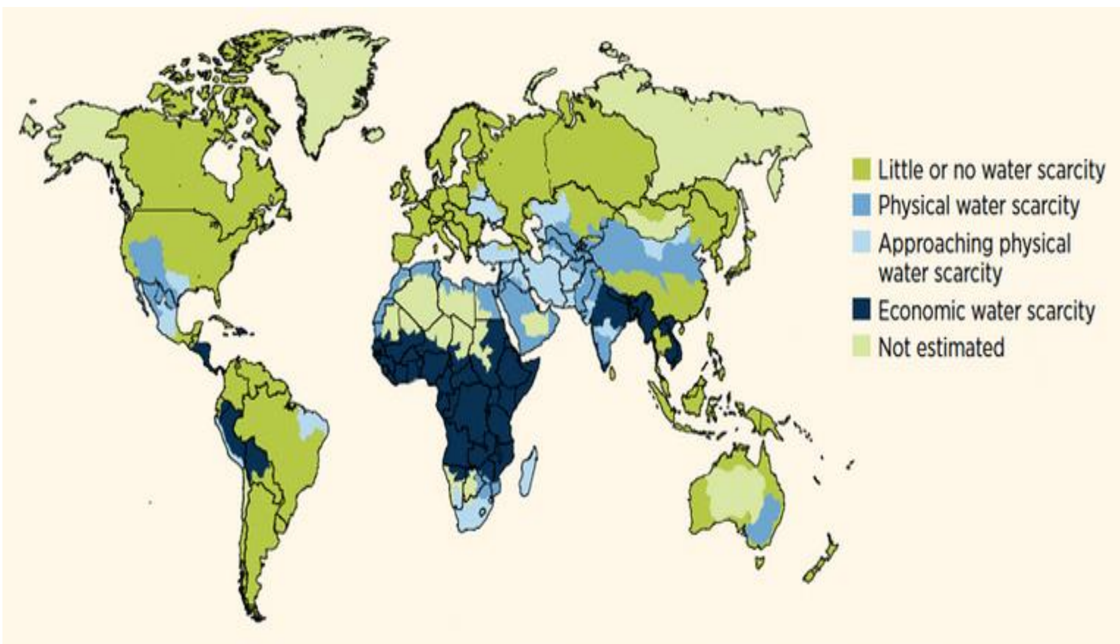


Figure 1: Global physical and economic water scarcity (WWAP, 2012)

1.2 Water Resources in the GCC

The Gulf Cooperation Council (GCC) is in an arid region where drought conditions prevail in the Arabian Peninsula in the Middle East. These oil-rich countries

— Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates are facing some of the most severe water shortages in the world (Al-Rashed, 2000). These regions have for long been known for higher temperatures and limited precipitation; water is ultimately a precious resource. The GCC region is classified as arid and hyper arid, and almost all these countries fall under the "absolute scarcity" threshold of 500 cubic meters of renewable water per capita per year. Rainfall scarcity and variability coupled with high evaporation rates limit the availability of renewable water resources. Climate change is projected to have major impacts in the water resources in the GCC; temperatures are expected to increase, while at the same time substantial decreases in precipitation are projected (IPCC, 2007) which would result in higher evapotranspiration. Another major factor in the GCC is the rapid population growth, and an accelerated socioeconomic development which have created increasing demands for water that cannot be met by these scarce renewable sources. Population growth and economic development, with associated increases in irrigation, domestic and industrial water requirements, might even be a bigger challenge for the GCC (Falkenmark and Lannerstad, 2005; Rosegrant et al., 2009). The GCC countries have exploited technology and built numerous desalination plants, but these remain capital intensive, costly, and with negative environmental impacts. Groundwater is being overexploited to meet mainly agricultural demands and recharge rates are much lower. The GCC countries also have the highest rate of water consumption in the world which could be associated with government subsidize prices or due to the nature of the hot weather, high rates of evaporation, high living standards etc.

The Food and Agricultural Organization (FAO) study estimates that 58% of the renewable water resources in the Middle East and North Africa will be used for food production by 2030 and far fetching efficiency measures are required (P. Droogers et al. 2012). Groundwater resources represents about 22% of all freshwater on earth; polar ice represents 77% while other freshwater in rivers and lakes represent about 0.3% (Bear et al., 1999). There are various uses of groundwater which includes: supplying water for domestic, industry and agriculture- the three most important sector of the society. Groundwater supplies about one-third of the world's drinking water and its importance is often underestimated. Groundwater is however not always available when and where needed, especially in water-shortage areas where heavy use has depleted underground reserves.

1.3 Physical Settings of the UAE

United Arab Emirates is located in the Middle East bordering the Gulf of Oman and the Arabian Gulf. It lies between 22°50′ and 26° north latitude and between 51° and 56°25′ east longitude with a total area of about 83 600 km^2, Figure 2. Climates in arid are characterize by limited rainfall, high temperatures, high humidity as well as high evapotranspiration. In the UAE, there are four climate zones (East Coast, Mountains, Gravel Plains and Desert Foreland) of distinguished rainfall distribution with an experience in rainfall deficit since 1999 (Sherif et al., 2014a). The land scape is composed of desert sand dunes and more than 75% is covered by the desert and mountainous areas with little natural vegetation. Its geomorphologic features include mountains, gravel plains, sand dunes, costal zones and drainage basins (Boer, 1997).

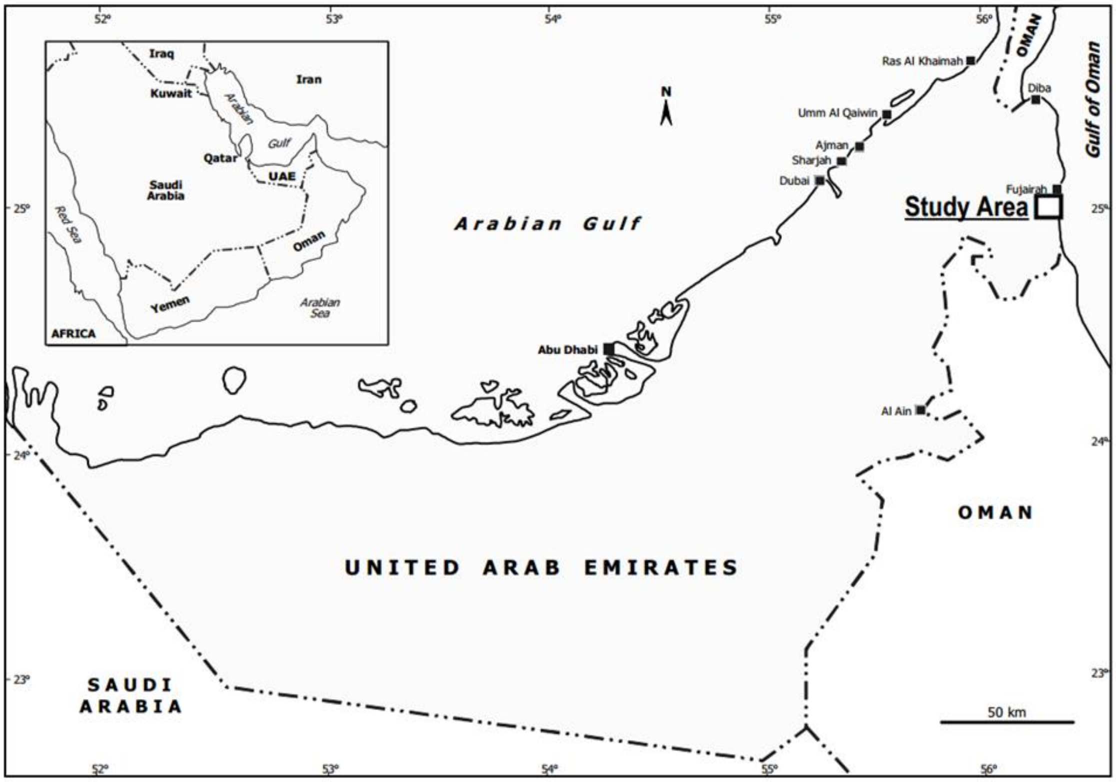


Figure 2: Location map of United Arab Emirates

1.4 Water Resources in the UAE

The UAE has limited water resources is faced with declining groundwater resources in both quantity and quality (AA Murad - 2010). There has been a rapid population growth from 4.1 million in 2005 to 8.9 million in 2012 (UAE National Bureau of Statics, 2014) in the UAE which has considerably led to an increase in water demand. This surge in population growth, increase agricultural activities, rise in living standards and industrial development increased the pressure on the limited available water resources. Overexploitation of groundwater for agricultural activities has resulted in increased water salinity from a phenomenon known as seawater intrusion. Excessive abstraction rates of groundwater; higher than natural or artificial recharges rates, is one cause of seawater intrusion. Low level of precipitation plus high temperatures has created severe shortage in the quantity of groundwater (AA Murad - 2010).

The UAE government in response to this dilemma has built and continues to build numerous expensive desalination plants to meet the growing demand for water. Production of desalination water in UAE has increased from 508.8 Mm^3 in 2000, to 1,790 Mm^3in 2012, (Ministry of Energy 2013 UAE) to cover the deficits of conventional water resources. Over the last two decades, farming activities have grown significantly due to the exploitation of groundwater in UAE. This has resulted in dramatic water table decline and deterioration in groundwater quality in some areas due to over-abstraction rates (M.A. Dawoud, EAD, 2008). Agricultural regions are mainly located within the eastern and northern parts of the country. In the UAE, agricultural activities consume about 80% of the available groundwater with a total usage of 950 Mm^3, 1,300 Mm^3 and 1,400 Mm^3 in 1990, 1995 and 2000, respectively (Murad et al., 2007). An increase in the cultivation areas will lead to an increase in water consumption for agricultural practices. Nevertheless, it is estimated that the annual renewable groundwater in UAE ranges from 130 Mm^3 to 190 Mm^3 (Murad et al., 2007). Therefore, groundwater resources consumption rates exceed the natural recharge, creating a deficit in groundwater availability.

1.5 Seawater Intrusion Problem

Coastal zones are among the most densely populated areas in the world with over 70% of the world’s population (Brown S. et al, 2013). These regions face serious hydrological problems such as: scarcity of freshwater, contamination of groundwater and seawater intrusion. The growing global population and rising standards of living have increased water demands and pumping from aquifers. In coastal aquifers, a hydraulic gradient exists toward the sea which leads to a flow of the excess freshwater to the sea. There is a zone of contact formed between the lighter freshwater flowing to the sea and the heavier underlying seawater; this is due to the presence of seawater in the aquifer formation under the sea bottom as shown in Figure 3.

Freshwater normally flows to the sea under naturally undisturbed conditions in coastal aquifer. Excessive pumping of freshwater from coastal aquifers leads to lowering of the water table or piezometric surface to the extent that the piezometric head in the freshwater body becomes less in the adjacent seawater wedge. And the interface could start to advance inland until a new equilibrium is reached. This phenomenon is known as seawater intrusion or encroachment. The advancement of the interface leads to the widening of the transition zone. The interface eventually contaminates inland pumping wells when it reaches them. A phenomenon called upconing toward the pumping well occurs when the pumping takes place in a well located above the interface. The continuous uncontrolled pumping could lead to seawater entering the pumped well and eventually the well might be abandoned due to high salinity levels. Seawater intrusion affects the groundwater quality and leads to deterioration of groundwater resources.

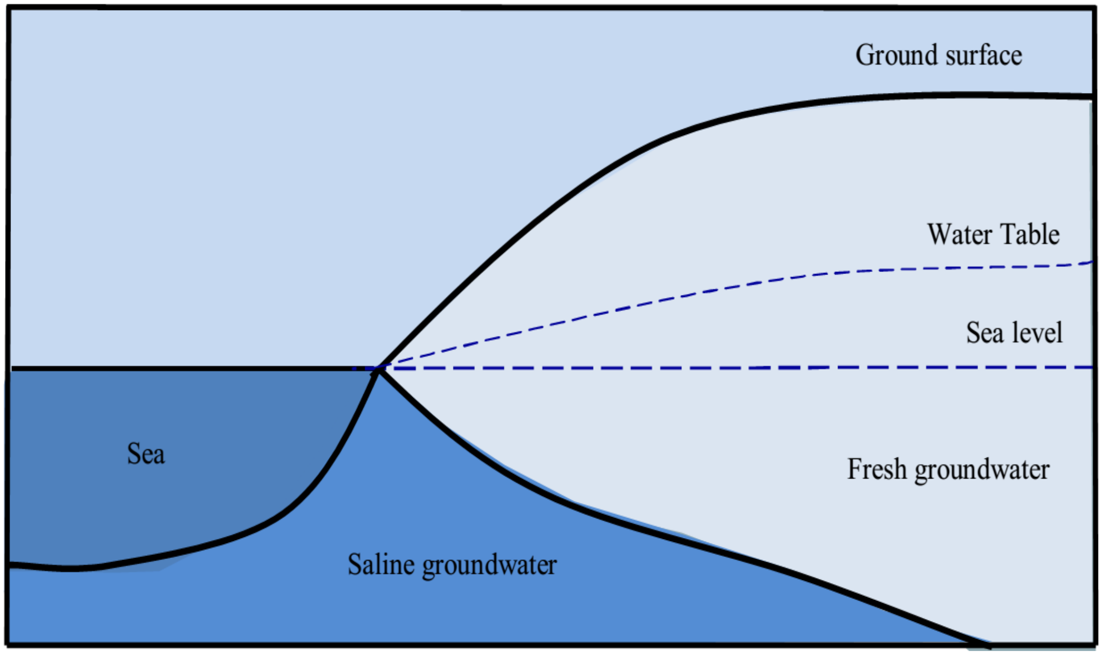


Figure 3: A cross section with interface under natural conditions

1.6 Study Area of Wadi Ham

The region of Wadi Ham is in the mountainous area immediately south and south east of the Masafi Mountains draining south east into the Gulf of Oman between Fujairah and Kalba. It is composed of valleys and steep slopes leading down to the Wadi floor of coarse alluvial gravels and boulders and deeply incised (Sherif and Kacimov, 2006). The Wadi Ham floor valley is a flat-gravelly plain with a triangular shape broadening to the sea and draining the surrounding mountains. It rises from sea level at Fujairah to approximately 100 m above sea level; to the northwest (Sherif and Kacimov, 2006). There are few hills scattered in different parts of the Wadi and subdivided into communicative zones. At upstream of the coastal plain, the land becomes a river terrace or alluvial plain. It is locally dissected by stream channels filled with cobble and gravel with the number and depth of channels decreasing towards the coast. Towards the coast, the wadi/coastal plain is used for extensive agricultural activities and new industries (Sherif and Kacimov, 2006).

Wadi Ham total catchment area is 192 km^2 with its upper part characterized by narrow valleys with distinct channels in the alluvial fill, and steep flanks along the surrounding peaks. At its lower eastern part, the catchment widens and forms a large fan until it reaches the sea. The catchment located in an arid region has limited freshwater resources. Its land use consists of natural arid region vegetation, irrigated farm lands and housing areas. Irrigation from groundwater is used in cultivated areas along the wadi streams and larger farming areas near the coast. Water demands for both domestic and agricultural uses are increasing while the quality and quantity of existing useable supplies are decreasing. The growing requirement of water in various consumption sectors in the coastal region of Kalbha and Fujairah is met by withdrawing large quantities of groundwater from the coastal aquifer of Wadi Ham. Over the last two decades there has been a decline in the groundwater levels in the coastal aquifer of Wadi Ham (Sherif, et al 2014). This decline is naturally associated with a significant deterioration in the groundwater quality due to the seawater intrusion and limited recharge. Many wells have already been terminated and several farms have been abandoned during the last decade in this coastal area due to intrusion of seawater into freshwater aquifers. The climate in the arid region is generally associated with low level of rainfall**.** There has been lower level of rainfall as shown in Figure 4 compared to previous years in Wadi Ham as reported by (Sherif et al. 2009, 2011) that average annual rainfall in Wadi Ham is around 150 mm/year, with a range between 20 and 506 mm/year. The review of rainfall records in the area over the last 10 years has shown that the average annual rainfall dropped to less than

80 mm which puts more pressure on available groundwater and natural recharge rates would significantly decrease.

(Sherif et al. 2014) developed a 2D finite element groundwater flow and solute transport model to simulate the spatial and temporal variations of the salinity distribution in the coastal aquifer of Wadi Ham. Total groundwater volume was estimated at 611.2 million m^3 of which only 153 million m^3 is fresh (Sherif et al. 2014). The results of their three simulated scenarios, of first simulating 2010 pumping rates and 50% reduction and increment in pumping rates in the second and third scenarios respectively as shown in Table 1**.** As presented in table 1, the volume of freshwater is expected to increase after 10 years of reduced pumping from 153 million m^3 to 205 million m^3 and it is expected to reduce from 153 to 124 million m^3 of increase pumping**.** The option of reducing the pumping is likely not feasible due to increasing water demand and the need for sustainable development in the region. An increase in pumping of freshwater would accelerate seawater intrusion and have undesirable consequences on the availability of freshwater. The combination of these issues amongst others poses a great challenge in coping with the decreasing water resources in the UAE particularly in this region of Wadi Ham.

Table 1: Simulated volumes of fresh, brackish, and saline water for scenarios 1 to 3 in 1988 (Sherif, et al 2014)

Scenario	Fresh		Brackish		Saline	
	Area (km^2)	GW-Volume (MCM)	Area (km^2)	GW-Volume (MCM)	Area (km^2)	GW-Volume (MCM)
1988	75.9	614.0	2.8	47.4	1.6	14.6
2010	44.8	153.0	16.6	183.0	18.9	275.6
2020 S1	45.0	151.1	16.6	184.4	18.7	278.6
2020 S2	49.9	205.2	14.2	172.8	16.6	248.1
2020 S3	44.3	124.2	13.5	189.3	21.8	293.6

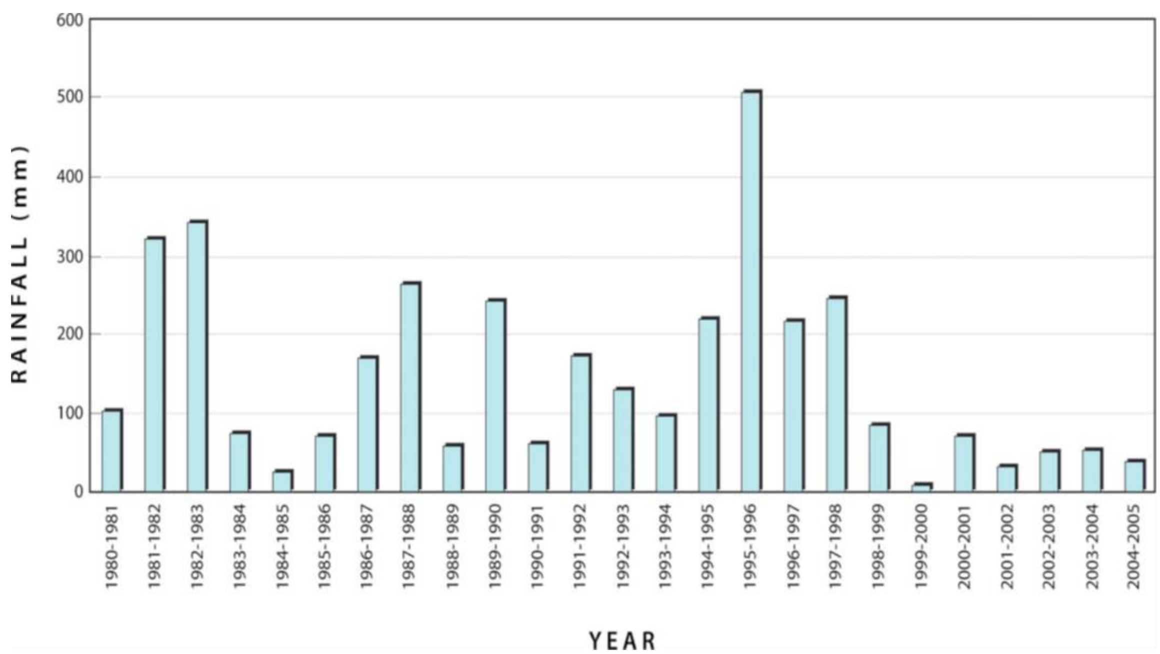


Figure 4: Distribution of mean annual rainfall, Wadi Ham (Sherif et al 2009)

1.7 Objectives of this Study

The main objective of this study is to link the benefit of pumping groundwater from the seawater intrusion zone- to hinder seawater intrusion- in the coastal aquifer of

Wadi Ham, UAE, to the needed quantities of water for desalination plants in the same area. Specific objectives of this study include the following:

1. Develop a transport model to simulate seawater intrusion in the coastal aquifer.

2. Conduct calibration and verification analysis of the developed model.

3. Investigate the effectiveness of pumping of brackish water from the coastal aquifer of Wadi Ham to reduce seawater intrusion.

4. Find optimum pumping rates and distances from the shoreline to minimize seawater migration towards the freshwater aquifer of Wadi Ham.

Chapter 2: Literature Review

2.1 Introduction

The problem of seawater intrusion (SWI) is one of the major challenges in water resource management. Global decline in freshwater resources couple with increasing freshwater demand from an increasing population makes the issue of SWI very critical. Seawater intrusion is a serious environmental problem for most coastal aquifers globally (Trabelsi et al., 2007; Sherif et al., 2012)**.** Seawater intrusion results from direct hydraulic contact between freshwater and saline water in coastal areas which leads to seawater migrating towards freshwater inland. The problem becomes more severe if the rate of freshwater extraction is higher than the natural or artificial recharge rates. Seawater intrusion is mainly caused by indiscriminate and unplanned groundwater exploitation for fulfilling the growing freshwater needs of coastal regions as more than two third of the world's population lives in these areas **(**Singh, 2014a). This problem leads to losses of freshwater resources and contamination of water supply wells. And this saline water becomes unsuitable for irrigation or its usage can result in modifying the soil chemistry and reduced soil fertility. Salinization of groundwater renders it unsuitable for domestic, agricultural and industries use even when a small quantity of 2–3% seawater mixing would degrade the groundwater quality (Abd-Elhamid and Javadi 2011).

The UAE located in an arid environment in the Arabian Gulf has limited water resources couple with scared rainfall and extreme climatic conditions; the problem of seawater intrusion becomes more severe. Groundwater resources contribute about 50% of UAE water demand while its quality and quantity is deteriorating and decreasing respectively due to heavy pumping with low recharge rates (Ahmed A. M 2010). It is evident that arid coastal regions are more vulnerable to groundwater deterioration problems due to extreme climatic conditions such as high temperatures, high humidity, and low precipitation rates. Water demand are prospected to increase globally especially in the arid regions where water resources have been known to be scare and limited. UAE is undoubtedly faced with increasing water demand due to increasing population and depletion of local water sources especially groundwater. The region of Wadi Ham located in the southern part of UAE represents one of the country's biggest water resource. Intensive groundwater abstraction from its coastal aquifer has resulted in seawater intrusion problem. Groundwater deterioration in the region has led to termination of wells which were sources of domestic water supply and essentially the abandonment of farms in the area. Seawater intrusion poses a great environmental challenge which threatens our most reliable source of freshwater. Continuous interaction between freshwater and saline water and other environmental factors change the groundwater quality distribution. This chapter gives an overall view of SWI problem including causes, investigation methods, control methods, etc.

2.2 Groundwater Contamination

Groundwater quality is an important issue in the development and management of water resources. In the face of an increasing demand for freshwater and intensification of its utilization; the quality problem becomes a limiting factor in the development and management of water resources in many parts of the world. Water quality of both surface and groundwater resources deteriorates when polluted and as such it is necessary to devote special attention to its pollution. Although, it seems that groundwater is more protected than surface water against pollution, groundwater is also subjected to pollution; and when polluted it is very difficult and costly to restore it to its original non-polluted state.

Groundwater pollution is usually traced back to four sources (Bear, 1979): First is environmental pollution; this type of pollution is due to the environmental characteristics through which the flow of groundwater takes place. For example, flow through carbonate rock, seawater intrusion and invasion by brackish water from adjacent aquifers. Second is domestic pollution; this type of pollution may be caused by accidental breaking of sewers, percolation from septic tanks, rain infiltrating through sanitary landfills, acid rains, artificial recharge using sewage water after being treated to different levels and biological contaminants such as bacteria and viruses. Third is industrial pollution; industrial pollution which may come from sewage disposal that contain heavy metals, non-deteriorating compounds and radioactive materials. And fourth is agricultural pollution; this is due to irrigation water and rain water dissolving and carrying fertilizers, salts, herbicides, pesticides, etc., as they infiltrate through the ground surface and replenish the aquifer. Main pathways and sources of groundwater pollutants are shown in Figure 5. Seawater intrusion is one of the most wide-spread and processes that degrades groundwater quality by raising salinity to levels exceeding acceptable drinking water and irrigation standards, and endangers future exploitation of coastal aquifers.

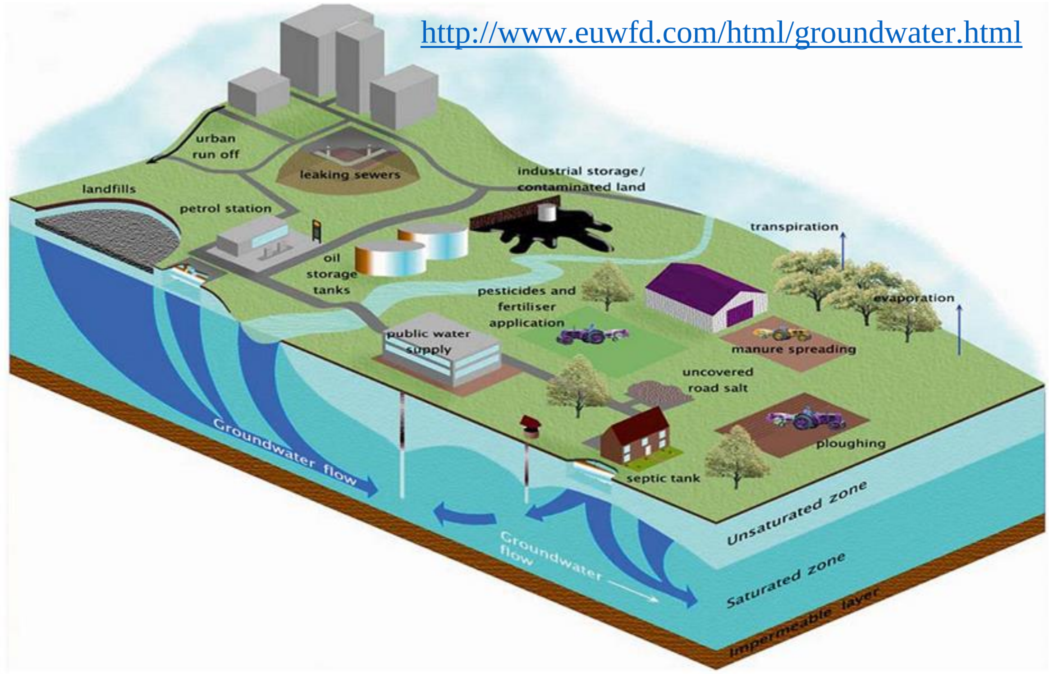


Figure 5: Main groundwater contaminant pathways and sources

2.3 Main Causes of Seawater Intrusion in Coastal Aquifers

There are various causes associated with seawater intrusion and most of them are caused by anthropological activities since about 70% of the world population live around coastal areas. Exploitation of groundwater is likely to increase under present increasing global population which puts more pressure on the limited available groundwater resources. Seawater intrusion may occur due to human activities, natural processes or because of the impacts of climate change through sea level rise. Some of the main causes of seawater intrusion includes: over-abstraction of the aquifers, seasonal changes in natural groundwater flow, tidal effects, barometric pressure, seismic waves, dispersion and climate change – global warming and associated sea level rise (Bear et al., 1999). The other causes of seawater intrusion include periodic such as seasonal changes in natural groundwater flow which could have either short-term implication in the form of tidal effects and barometric pressure; or long term implications in the form of climate changes and artificial influences. Intrusion of seawater should be controlled to protect groundwater resources from depletion as it is a major limitation to its utilization. The control of seawater intrusion requires an in-depth study from both theoretical or numerical analysis and practical point of view.

2.4 Seawater Intrusion Investigation Methods

Geological and hydrochemical characteristics of aquifers are important components in assessing seawater intrusion in coastal aquifers and its information is required in the analysis of salinization process. Geophysical and geochemical methods are among several methods used to investigate seawater intrusion in coastal aquifers. Experimental studies, analytical and numerical models are also used in investigation methods. The main aim of these approaches is to ascertain the position of freshwater/seawater interface and predict changes in water levels and salinity. These methods are briefly discussed as follows.

2.4.1 Geophysical Investigations

Total dissolved solids (TDS) is a major indicator of seawater intrusion as it can be distinguished by the movement of water with high (TDS) content into freshwater. There is a variation in the degree of salinity in the transition zone between fresh and saline groundwater. Contour map of TDS is one measure of salinity and location of contour TDS=1000 mg/l marks the area under seawater intrusion influence. Table 2 shows description of water type based on TDS content suggested by USGS.

Geophysical methods measure the spatial distribution of physical properties of the earth, such as bulk conductivity of seismic velocity. There have been various studies conducted by numerous researchers who used geophysical methods to investigate seawater intrusion. Some of these studies include; a study conducted by (Melloul and Goldenberg 1997) in which they analyzed different methods of monitoring seawater intrusion in coastal aquifers. They used direct methods of groundwater measurement salinity profiles and groundwater sampling observation and pumping wells, and indirect methods using geo-electromagnetics and the time domain electromagnetic method. (Sherif et al. 2006a) used a 2-D earth resistivity survey to delineate seawater intrusion. Another study was done by (Levi et al. 2010) whose aim was to delineate the expected saline water intrusion from estuarine rivers into adjacent aquifers by means of high resolution and accurate geoelectric/geo-electromagnetic methods. They used combined high resolution electrical resistance tomography and accurate time domain electromagnetic measurements to study the relationships between seawater and groundwater via estuarine rivers at two sites along the lower part of the Alexander river in Israel. (Sherif et al. 2010) also using geophysical techniques presented field investigations and measurements that revealed the nature and extent of seawater intrusion in the coastal aquifer of Wadi Ham, UAE. They presented a 3D geological and true earth resistively modelling for the aquifer. The results obtained from the earth resistivity imaging surveys and chemical analyses of the collected water samples were used to obtain an empirical relationship between the inferred earth resistivity and the amount of total dissolved solids.

Table 2: Water type based on TDS content (USGS)

TDS (ppm) or (mg/l)	**Description**
<1000	Freshwater
1000-3000	Slightly saline
3000-10000	Moderately saline
10000-35000	Very saline
>35000	Brine

2.4.2 Geochemical Investigations

Geochemical investigations involve the use of tools and principles of chemistry to explain seawater intrusion mechanism within the geological systems of the earth and oceans. There are distinct characteristics of different salinization mechanisms which are crucial to the evolution of the origin, pathways, rates and future salinization of coastal aquifers. Several geochemical criteria can be used to identify the origin of salinity in coastal aquifers (Bear et al., 1999):

1- Cl-concentration: the Cl-concentration of 200 mg/l in groundwater is used as index of seawater intrusion.

2- Cl/Br ratios: the bromide ion can be considered as a good indicator of seawater intrusion. Concentration of bromide in freshwater is less than 0.01 mg/l.

3- Na/Cl ratios

4- Ca/Mg, Ca/ (HCO3+SO4) ratios

5- O and H isotopes

6- Boron isotopes

Geochemical criteria used for distinguishing seawater origin shown in Table 4. A hydrochemical study was conducted by (Zubari 1999) to identify sources of aquifer salinization and delineate their area of influence. The extent of seawater intrusion was examined using vertical electrical sounding and hydrochemical data into shallow aquifers beneath the coastal plains of south eastern Nigeria (Edet and Okereke 2001).

2.4.3 Experimental Studies

Experimental methods have also been exploited in the investigation of seawater intrusion by some researchers. An in-situ laboratory was developed in an integrated set of tools for characterizing the seawater intrusion process in a hard rock aquifer with an appreciable level of heterogeneity (Van Meir et al. 2004). The final aim of the geophysical and hydraulic investigations was to derive 3-D porosity and permeability models as input for the analysis of specific seawater intrusion experiments. (Mukhopadhyay et al. 2004) presented a laboratory study to investigate the effects of artificial recharge on the aquifer material properties such as; porosity and permeability in group aquifer of Kuwait. The used of inactive cells was also employed by **(**Motz 2004) in which he used inactive cells to present the seawater part of the aquifer and a no-flow boundary along the interface. Then he performed series of numerical experiments to investigate how the seawater-freshwater interface should be approximated in a groundwater flow model to yield accurate values of hydraulic heads in the freshwater zone. These studies amongst others provide insightful information on experimental studies conducted to investigate seawater intrusion problem.

2.4.4 Mathematical Models

Mathematical models are important components in understanding as wells as dealing with the seawater intrusion problem. They have for long been used to understand the mechanism of SWI in coastal aquifers. There have been various analytical and numerical models developed to investigate the seawater intrusion problem in coastal aquifers. A finite element model for flow and solute transport was developed by (Sheriff et al. 1990) to investigate the effect of lowering piezometric head due to excessive pumping on the saline water intrusion. In another study, a finite element model meant to simulate hydrodynamics of flow and salt transport in well-mixed estuaries to reduce the undesirable impacts of seawater intrusion was developed by (Ghafouri and Parsa 1998). Movement of freshwater/seawater and the depth of freshwater/seawater interface in coastal aquifers was predicted using a numerical groundwater model (Tsutsumi et al. 2001). Numerical models have been used to simulate seawater intrusion in shallow confined aquifers (Teatini et al. 2001). For example, (Vazquez et al. 2004) developed a numerical model to investigate seawater transport in Llobregat delta aquifer, Barcelona, Spain. The development and application of mathematical model in the investigation and mitigation of seawater have for long being exploited by researchers as highlighted above.

2.5 Methods of Seawater Intrusion Modeling

Modeling of seawater intrusion has been an important tool in assessing and controlling seawater intrusion. The two basic principles used in the study of seawater intrusion are the sharp-interface and density-dependent model.

2.5.1 Sharp-Interface Models

This section explains the principle under which sharp-interface model operates which was first developed independently by (Herzberg 1901and Ghyben 1988). This model was simply known as the Ghyben-Herzberg model and is based on the hydrostatic equilibrium between fresh and saline water as shown in Figure 6, and is described by Ghyben-Herzberg equation as;

$$hs = \left(\frac{pf}{ps-pf}\right) hf \tag{2.1}$$

Where:

ps: is the seawater density

pf : is the freshwater density

hs: is the depth of the interface below mean sea level

hf: is the height of the potentiometric surface above the mean sea level

According to the Ghyben-Herzberg equation, if the seawater density is 1025 kg/m^3 and freshwater density is 1000 kg/m^3, this gives hs = 40 hf

Gyben-Herzberg principle on which the sharp-interface models is based on assumes a sharp interface between fresh and saline groundwater. This suggest that the width of freshwater-seawater mixing zone is much smaller than the thickness of the aquifer, and therefore assumed that freshwater and seawater are two immiscible fluids of different, but constant densities separated by an interface. The assumption that the interface between seawater and freshwater has a sharp and a well-defined interface is not realistic in practice as seawater merges gradually with the freshwater by the process of mechanical dispersion. The width of dispersion zone depends on the characteristics of the aquifer and movement of water particles due to tides or fluctuation due to recharge (Cooper, 1959). This assumption can however be applied in some field conditions to obtain a first approximation to the freshwater pattern if the transition zone is relatively narrow otherwise dispersion process should be considered and entrainment of seawater by moving freshwater is necessary to describe the phenomena (Kohout, 1960).

There have been numerous models developed base on the principle of sharp interphase which aimed to predict the interface or transition zone between freshwater and seawater. The one-fluid models are based on freshwater dynamics only which were used by (Glover 1959), Henry 1959, Shamir and Dagan 1971, Volker and Rushton 1982, and, Ayers and Vacher 1983). They all assumed that the water table and the sharp interface maintain continuous equilibrium and that the seawater is static. Several researchers used the sharp interface assumption to model seawater intrusion. (Sbai et al. 1998) used the finite element method for the prediction of seawater intrusion under steady state and transient conditions based on a sharp interface model assuming the freshwater and seawater to be immiscible. (Izuka and Gingerich 1998) presented a method to calculate vertical head gradients using water head measurements taken during drilling of a partially penetrating well. They then used the gradient to estimate interface depth based of Ghyben-Herzberg relation. An optimization technique was used to determine the location of sharp interface between seawater and freshwater (Naji et al. 1998). The algorithm they used was based on the combination of nonlinear programming and h-adaptive boundary element method. (Aharmouch and Larabi 2001) presented a numerical model based on the sharp interface assumption to predict the location, shape and extent of the interface that occur in coastal aquifer due to groundwater pumping. (Taylor et al. 2001) presented a comparison between results of different codes applied to Henry's problem and analyzed the sensitivity of each code to changes in the parameters. These studies among others showed that the sharp-interface approach has been successfully used by researchers**.**

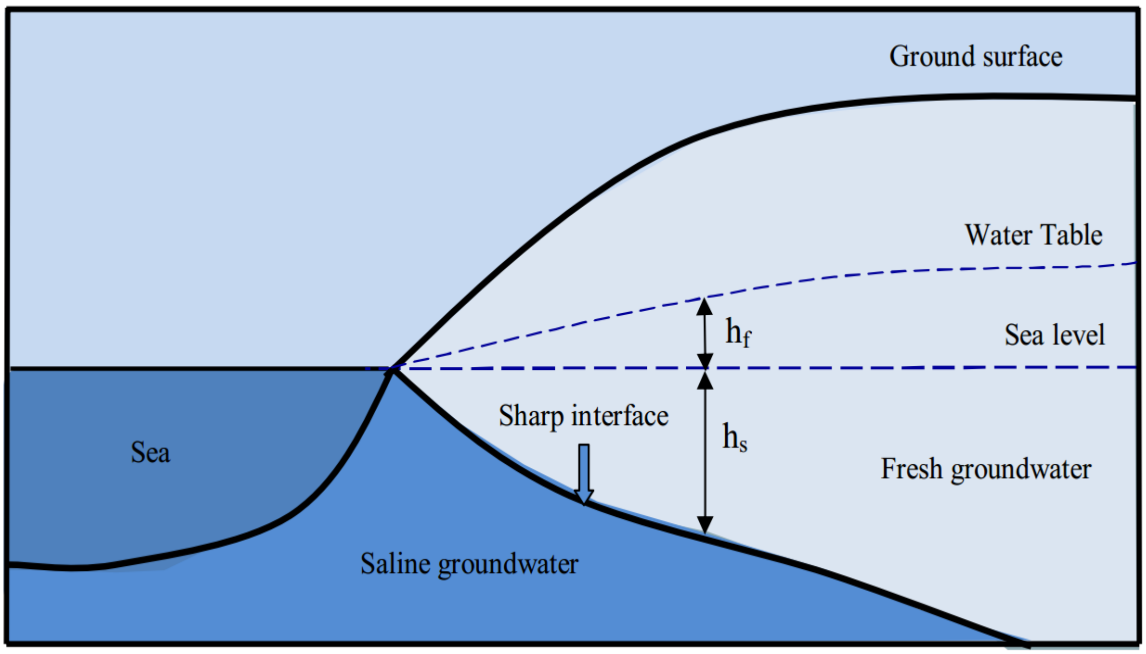


Figure 6: Hydrostatic equilibrium between fresh and saline water

2.5.2 Density Dependent Models

Density-dependent model is based on advective–dispersive density-dependent steady-state miscible flow and transport processes. The model considers freshwater and seawater mixing and explicitly allows change in water density by solving coupled flow and transport equations simultaneously. This model better describes the actual seawater intrusion mechanism due to strong seawater hydrodynamic dispersion and the existence of a wide transition zone and which is the case in real coastal aquifers. The two simultaneous processes that gave rise to density-dependent seawater circulation in coastal aquifers (Bear, 1972; Reilly and Goodman, 1985; Bobba, 1993): (1) displacement of relatively fresher groundwater by denser marine water and (2) hydrodynamic dispersion of salt within the seawater-freshwater mixing zone. Hydrodynamic dispersion and diffusion tend to mix the two fluids forming a transition zone at the interface as shown in Figure 7. Transition zone depends on the extent of seawater intrusion and aquifer properties. This transition zone depends on the hydrodynamic dispersion of the dissolved matter and could be wide or narrow according to the aquifer depth. Steady flow minimizes the transition zone thickness, whereas pumping, recharge, tides and other excitations increase its thickness. Thickness of transition zones could range from a few meters to several kilometers in over-pumped aquifers. The thickness of a transition zone depends on structure of the aquifer, extraction from the aquifer, variability of recharge, tides, and climate change (Todd 1974).

There are number of mathematical models developed to simulate seawater intrusion base on the density dependent principle. (Tasi and Kou 1998) developed a two-dimensional finite element code, considering density-dependent flow and transport. The model was used to simulate seawater intrusion and to evaluate the major effects of hydrological and geological parameters, including hydraulic conductivity, hydraulic gradient on seawater intrusion. (Benson et al. 1998) studied the effect of velocity gradient on solute transport. Their study showed that in case of seawater intrusion, the velocity is so high and hence affects the solute transport. Other numerical models assume approximate value of the velocity due to its low value. (Cheng et al. 1998) developed a 2-D finite element model for density dependent flow and solute transport through saturated and unsaturated soils. (Sakr 1999) presented a finite element model to simulate density-dependent and solute transport. These models have recently attracted more attention from researchers since they are more realistic.

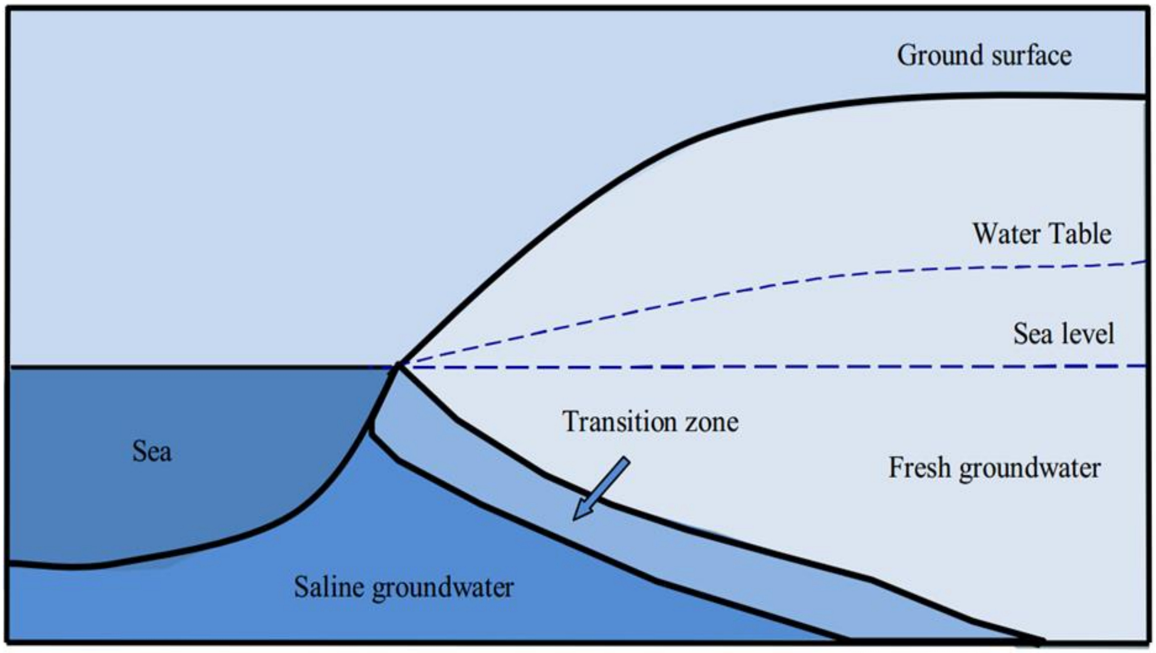


Figure 7: Location of transition zone

2.6 Seawater Intrusion Control Methods

Seawater intrusion is major a contaminant of groundwater resources; a major source of livelihood for most people on earth. There has been considerable effort to control seawater intrusion in coastal aquifers for the protection of groundwater resources and numerous methods have been investigated. The control of seawater intrusion represents a continuous challenge because groundwater provides about one-third of the total freshwater consumption in the world especially in the coastal areas, where 70 % of the world population lives (Bear et al., 1999). Seawater intrusion is one of the major issues of concern in the management of groundwater resources globally and extensive research has been conducted in its mechanism and mitigation strategies. There are various studies conducted for the mitigation of seawater intrusion among which includes the reduction of abstraction rates that aims to reduce the pumping rates and use other water resources (Scholze et al. 2002). The relocation of abstraction well which aims to move the wells further inland (Sherif and Al-Rashed 2001). Subsurface barriers aim to prevent the inflow of seawater into the basin (Harne et al. 2006). Other studies include maximization of the total pumping rate (Abarca et al., 2006; Singh, 2012), minimization of seawater volume into the aquifer (Hallaji and Yazicigil, 1996), minimization of drawdown (Emch and Yeh 1998), minimization of pumped water salinity (Das and Datta, 1999b) etc.

The main objective of seawater intrusion control is to maintain a proper balance between water being pumped from the aquifer and water recharged to the aquifer. There has been number of methods used to control seawater intrusion, however they are not all feasible economically and environmentally. (Todd 1974) presented various methods of preventing seawater from contaminating groundwater sources including:

1- Reduction of pumping rates

2- Relocation of pumping wells

3- Use of subsurface barriers

4- Natural recharge

5- Artificial recharge

6- Abstraction of saline water

7- Combination techniques

2.6.1 Reduction of Pumping Rates

Pumping of freshwater for various purposes without adequate recharge is the main cause of seawater intrusion as it disturbs the natural balance between freshwater and seawater. Continues pumping of freshwater lowers the groundwater levels and therefore reduce the amount of freshwater flowing into the sea, and eventually causes seawater to intrude into the coastal aquifer. Thus, over-abstraction of freshwater is regarded as the main cause seawater intrusion in coastal aquifers. Reduction of pumping rates can maintain a natural balance between the freshwater and seawater, however under increasing demand for water from an increasing population; reducing the rates of pumping would be critical. Reducing the pumping rates aims to achieve sustainable yield and use other water resources to supply adequate water demand.

This can be achieved by several measures including:

1- Increase in public awareness of the necessity to save water,

2- Reduction of losses from the water transportation and distribution systems,

3- Reduction of water requirement in irrigation by changing the crop pattern and using new methods for irrigation such as drip irrigation, canal lining, etc.,

4- Recycling of water for industrial uses, after appropriate treatment,

5- Reuse of treated wastewater in cooling, irrigation and recharge of groundwater, and

6- Desalination of seawater.

Models have been developed to control seawater intrusion by reducing pumping rates from the aquifer or using optimization models to optimize the abstraction and control the intrusion of saline water. There is agreement that reducing the pumping rates would halt seawater intrusion and ultimately restore the balance between seawater and freshwater. The main advantage of reducing pumping is that it to increase the volume of freshwater which retards the intrusion of seawater. This system presents various disadvantages; under increasing demand for water, controlling the pumping rate cannot be fully achieved and would be an uneasy idea with most stakeholders. The use of alternative sources may be too expensive especially if the freshwater needs to be transported, another costly alternative is desalination which also generates other environmental challenges and poses a big challenge of sustainability. Reduction of pumping rates to control seawater intrusion can be considered a temporal solution as it does not prevent seawater intrusion but it attempts to reduce it. And with the increase in population growth and increasing demands; the problem will not be controlled (Abd-Elhamid and Javadi, 2008a).

2.6.2 Relocation of Pumping Wells

Relocation of pumping wells is done when wells are contaminated with seawater, this prompts their relocation to a more inland position which aims to raise the groundwater level and maintain groundwater storage. This is because in the inland direction, the thickness of the freshwater lens increases and the risk of upconing of seawater decreases accordingly. A study by (Ofelia et al. 2004) used a mathematical model to identify seawater volume interred the fresh groundwater in Santa Fe, Argentina. They examined a management model to protect the fresh groundwater system in which several pumping wells were removed and new wells constructed. (Hong et al. 2004) developed an optimal pumping model to evaluate optimal groundwater withdrawal and the optimal location of pumping wells in steady-state condition while minimizing adverse effects such as water quality in the pumping well, drawdown, seawater intrusion and upconing. Their study involved experimental verification of the optimal pumping model to develop sustainable water resources in the coastal areas. (Sherif et al. 2001) used two models which are 2D-FED and SUTRA to simulate the problem of seawater intrusion in the Nile Delta aquifer in Egypt in the vertical and horizontal directions. 2D-FED model was used to simulate the current condition and predict the effect of seawater level rise in the Mediterranean Sea considering the condition of global warming. SUTRA model was used to define the best location of additional groundwater pumping wells from the Nile Delta aquifer and to assess the effect of various pumping scenarios on the intrusion process.

The decrease occurrence of upconing of seawater is the main advantage of relocating wells inland (Abd-Elhamid and Javadi, 2008a). This method is costly and may face some obstructions such as, buildings or the size of the aquifer may not allow such movement. It is also a temporary solution and does not prevent the intrusion of saline water into the aquifer.

2.6.3 Subsurface Barriers

This method involves the construction of physical barriers to control seawater by reducing the permeability of the aquifer and preventing the inflow of seawater into the basin. Materials that could be used for construction includes using sheet piling, cement grout, or chemical grout. A sketch of a subsurface barrier used to control seawater intrusion is shown in Figure 8. This method main challenge is the fact that it is costly to implement. A study by (Barsi 2001) aimed at finding the optimal design of subsurface barrier to minimize the total construction cost through the selection of width and location barrier. This was demonstrated by the development of two methods for optimal design of subsurface barriers to control seawater intrusion through the development of implicit and explicit simulation-optimization models. Another study conducted by (Harne et al. 2006) in which they presented a 2-D subsurface model of seawater considering the soil to be homogenous and isotropic under the influence of constant seepage velocity. The objective of this model was to examine the efficiency of subsurface barrier to control seawater intrusion.

The main advantage of using subsurface barriers is that it helps to reduce saline water intrusion. On the other hand, this system is costly in terms of construction, operation, maintenance, and monitoring. And it is not efficient for deep aquifers (Abd-Elhamid and Javadi, 2008a).

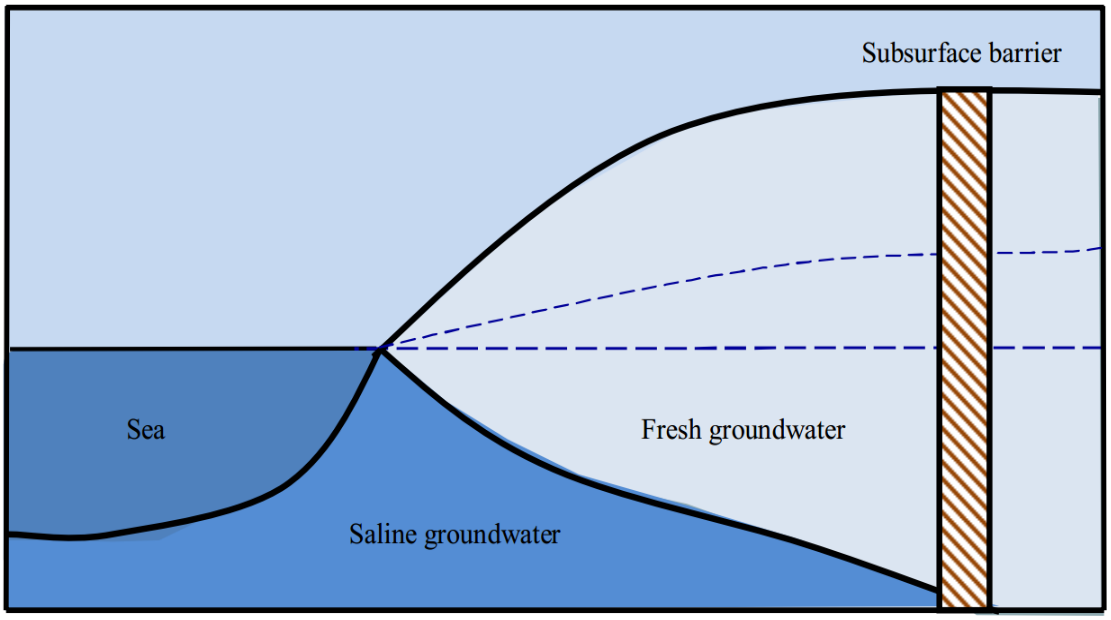


Figure 8: Sketch of a subsurface barrier

2.6.4 Natural Recharge

This system works by constructing dams and weirs to prevent the runoff from flowing to the sea and ultimately recharging it naturally to the aquifer through infiltration of the holdup water. This allows the additional feeding of surface water to aquifers, essentially increasing the volume of the groundwater and it can also be used as a flood protection. Figure 9 shows a sketch of the natural recharge process. This system is highly depended on the soil properties and geological setup of the recharge area. It could be an efficient method for recharge of unconfined aquifers but it could take a long time to recharge the aquifer depending on its properties. Recharging the aquifers would help maintain balance between seawater and freshwater in the aquifer and ultimately control seawater intrusion. The effects of constructing a dam to protect groundwater resources was evaluated using a quasi-3-dimensional model which simulated the movement of the interface between seawater and freshwater, (Ru et al. 2001). The subsurface dam was used to collect the rain water and recharge the aquifer to increase the groundwater storage and ultimately retarded seawater intrusion.

The main advantage of this method is that it helps prevent runoff to flow directly to the sea and uses it to increase the groundwater storage in the aquifer and prevent the intrusion of saline water. This method is highly dependent on the soil properties as the rate of permeability varies from one soil characteristics to the other and high permeability is required in this case for effective infiltration. And the cost of constructing dams and weir as well as their operation and maintenance is very costly. This system also requires wide area for construction and it is not suitable for confined and deep aquifers.

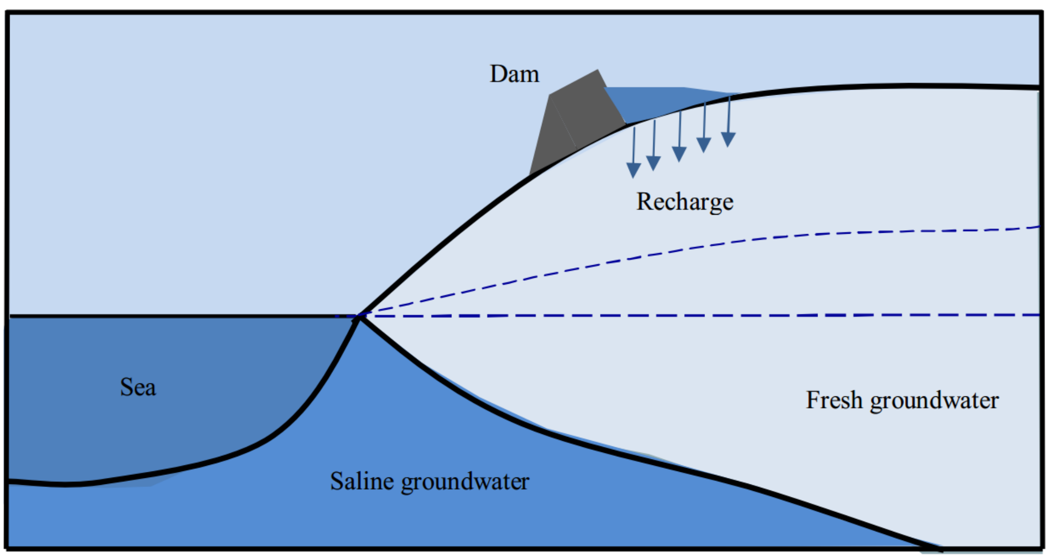


Figure 9: Sketch of the natural recharge process

2.6.5 Artificial Recharge

Artificial recharge is aimed at supplementing natural groundwater recharge since abstraction rates are usually higher than natural recharge rates; which is the main cause of seawater intrusion. Artificial recharge involves the use of surface spread for unconfined aquifers and recharge wells for confined aquifers. Aquifer recharge is normally expected to increase the groundwater levels. The main sources of water for groundwater recharge ranges from surface water, pumped groundwater, desalinated seawater, brackish water and in some places treated wastewater. Pipelines are used to draw water from surface water bodies and then injected into the aquifers.

(Narayan et al. 2006) used SUTRA to define the current and potential extent of seawater intrusion in the Burdekin Delta aquifer under various pumping and recharge conditions. They developed 2-D vertical cross-section model for the area, this accounted for groundwater pumping and artificial recharge schemes. The results showed the effects of seasonal variation in pumping rate and artificial and natural recharge rates on the dynamic of seawater intrusion. (Kashef 1976) studied the effects of recharge wells of different patterns on the degree of seawater retardation in confined coastal aquifers. He equally spaced the recharge wells at various distances parallel to the shoreline. (Mahesha 1996b) presented steady state solutions for the movement of the freshwater/seawater interface due to a series of injection wells in a confined aquifer using a sharp interface finite element model. This model examines the effects of injection wells location using parametric studies and results showed that reduction of seawater intrusion (of up to 60-90 %) could be achieved through proper selection of injection rate and spacing between the wells.

Artificial recharge helps to increase the groundwater storage in the aquifer and prevent the intrusion of saline water. Despite its effectiveness in controlling seawater intrusion; source of freshwater for artificial recharge remains a challenge. Freshwater is not readily available for recharge in most areas and transporting it to other locations for recharge would be a daunting challenge. The use of desalinated water is not only expensive but also contains potentials pollutants to the groundwater. Treated wastewater could also be a good alternative but it is costly and ineffective in the areas where excessive groundwater pumping occurs (Narayan et al. 2002 and Narayan et al. 2006).

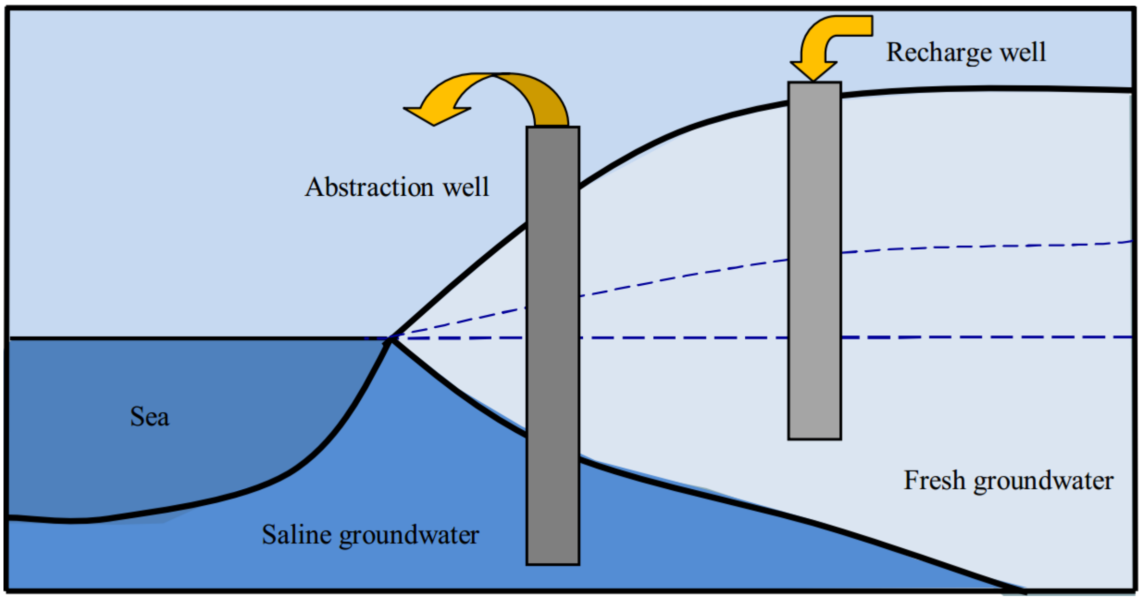


Figure 10: Sketch of recharge and abstraction wells

2.6.6 Abstraction of Saline Water

This method involves the pumping of saline water from the aquifer near the dispersion zone and then reusing the water for desalination. The aim of this method is to reduce the volume of the saline water and halt intruding saline water and eventually improving the fresh groundwater quality as demonstrated in Figure 10. This was demonstrated by (Sherif and Hamza 2001) in which they developed a finite element model (2D-FED) considering dispersion and variable density flow to simulate the effect of pumping brackish water from the transition zone. Their study was aimed at restoring balance between the freshwater and saline water in the coastal aquifer. The pumped water could be desalinated otherwise disposing it could pose a challenge. They proposed different solutions to overcome the problem of disposing excess or un-desalinated seawater; among which includes cooling, desalting, injection into deep wells, irrigation, or disposal to the sea. This method was used in California, USA as one of the methods (Johnson and Spery 2001) in which they extracted saline water and desalinated using RO treatment for domestic delivery. Treated water was mixed with untreated groundwater to produce suitable water for domestic delivery. This mixed water could also be used for artificial recharge as in Los Angeles injection wells were used to protect the coastal aquifers from seawater intrusion. Pumping of saline water mitigated seawater intrusion (Maimone and Fitzgerald 2001, Sherif and Kacimov 2008, Kacimov et al. 2009). Both analytical and numerical models proved that pumping of saline groundwater from coastal aquifers would mitigate the migration of seawater into the aquifer and would contribute to the enhancement of the groundwater quality that is consistent with the findings (Sherif and Hamza 2001).

Main advantage of abstracting the saline water is that it decreases the volume of the saline water, halt its intrusion to freshwater and protects pumping wells from upconing and ultimately improving groundwater quality. The main constraint of this method is the disposal of the pumped saline water as it is not suitable for the irrigation of most crops and could cause corrosion to systems when use in cooling. Optimum pumping location as well as pumping rates and duration is still under study of which this study aims to include. Another problem is that increasing abstraction of saline water could, in some cases, increase the intrusion of seawater (Abd-Elhamid and Javadi, 2008a).

2.7 Proposed Method of Pumping Brackish Water

The options discussed above could be feasible in the control of seawater intrusion, however, these options might not be cost effective economically and not environmentally viable due to natural environmental settings. Various methods considered in previous studies in the control and management of seawater intrusion in the study area excluded the propose method. Pumping of brackish water is a technique that aims at restoring balance between freshwater and saline water in coastal aquifers to mitigate the seawater intrusion problem. Brackish water can be pumped from the dispersion zone for a specified period at a certain discharge rate and this pumped water can either be use for desalination or to irrigate crops with higher salt tolerance. This method of abstraction is expected to reduce the intrusion of saline water which can lead to the displacement of the dispersion zone towards the coast. The process will continue until a state of dynamic equilibrium is reached with respect to the salinity distribution. Pumping of brackish groundwater from coastal aquifers would mitigate the migration of seawater deep into the aquifer and would contribute to the enhancement of the groundwater quality (Sherif and Hamza 2001). (Rastogi et al. 2004) reported that the combination of injection of freshwater and extraction of saline water can reduce the volume of seawater and increase the volume of freshwater. A series of three dimensional numerical simulations using multidimensional hydrodynamic dispersion models were developed by (Park et al. 2012). In their study, they considered series of seawater extraction schemes for the mitigation of seawater intrusion attributed to groundwater pumping.

This method of pumping brackish water to mitigate seawater intrusion is not yet well understood due to existing knowledge gap in terms of the required discharge rates at optimum pumping locations and at specified time durations analysis (Sherif and Hamza 2001). To the best of our knowledge there are few studies conducted to assess the effectiveness of pumping brackish water to mitigate seawater intrusion. The studies conducted only highlighted its potentiality as an option to mitigate seawater intrusion but no comprehensive study to determine its effectiveness considering various factors such pumping location, abstraction rates and intensity, duration required and cost analysis. The optimum pumping location required for the reduction, or displacement of the saline water towards the coast to eventually maintain or push the dispersion zone towards the coast has not been specified in any of these studies. This study aims to investigate these issues which could be an important step in overcoming or coping with the growing water scarcity in the study area.

Chapter 3: Groundwater Modeling

3.1 Introduction

Models can be defined as conceptual descriptions that represent or describe an approximation of a field situation, real system or natural phenomena. They are applied to a range of environmental problems to evaluate, understand and interpret issues having complex interaction of many variables in the system. Although, they are not exact descriptions of physical systems or processes but are mathematically able to represent a simplified version of a system (Bear, J. 1979). Groundwater models describe the groundwater flow and transport processes using mathematical equations based on certain simplifying assumptions. They are mainly used in calculating rates and direction of groundwater flow in an aquifer. Some of the main assumptions considered includes flow direction, geometry of the aquifer, heterogeneity or anisotropy of sediments or bedrock within the aquifer, the contaminant transport mechanisms and chemical reactions. These assumptions help in simplifying and schematizing real systems (Bear, J. 1979). Models have been applied to investigate a wide variety of hydrogeologic conditions including the understanding of flow systems and their relationships with other systems as well as providing answers to different exploitation scenarios.

Modeling of saturated flow in porous media is generally straightforward with few conceptual or numerical problems while the application of flow models involving two or more liquids in porous media is more complicated in terms of the process and parameters involved. Nevertheless, such models have been applied successfully (Anderson, M.P. and W.W. Woessner, 1992). Models are basically conceptual descriptions or approximations that describe physical systems using mathematical equations. Models, mathematically represents a simplified version of hydrogeological systems to predict, test, and compare reasonable alternative scenarios. The accuracy of model is highly depended on how close mathematical equations approximate the physical system being modeled. It is therefore imperative to thoroughly understand the physical system been modeled and the assumptions embedded in the derivation of the mathematical equations. Generally models are viewed has approximations of field situations; however, they are useful tools that groundwater hydrologist use for several applications. They are used in several applications such as water balance studies- in its quantity, understanding it quantitative aspects of the unsaturated zone, simulation of water flow (Domenico, P.A., 1972). They can also be applied to study chemical migration in the saturated zone such as seawater intrusion, investigating the effects of changes of groundwater regime on the environment, setting up/optimizing monitoring networks, and setting up groundwater protection zones.

3.2 Groundwater Modeling Methods

Groundwater models are used to describe and evaluate groundwater systems in a more simplified way. They can either be physical or mathermatical; physical models replicates physical processes usually on a smaller scale than encountered in the field. The simulation of groundwater flow requires a comphensive understanding of hydrogeological characteristics of the site been modelled. This is so to increase the closeness of the approximation of mathematical equations of physical system being modelled. Model applicability and reliability is highly depended on the approximation of mathematical equations describing the physical system. Hydrogeologic framework such as aquifer thickness, confining units, boundary conditions and hydraulic properties such as hydraulic head, groundwater recharge, discharge, and sources or sinks of the modelled aquifer should be well defined and understood. Groundwater modelling entails simulation of aquifer and its response to input/output systems. Figure 11 shows the different steps in hydrological model application.

The two main methods employed in solving governing equations for groundwater systems are either analytically or numerically. Analytical models contain analytical solution of the field equations, continuously in space and time. Numerical models on the other hand obtains a discrete solution in both space and time domains by using numerical approximations of the governing partial differential equation. There are different models used to solve the equations that describes the groundwater-flow and fate-and-transport processes which are analytical and numerical models which are disscuss below.

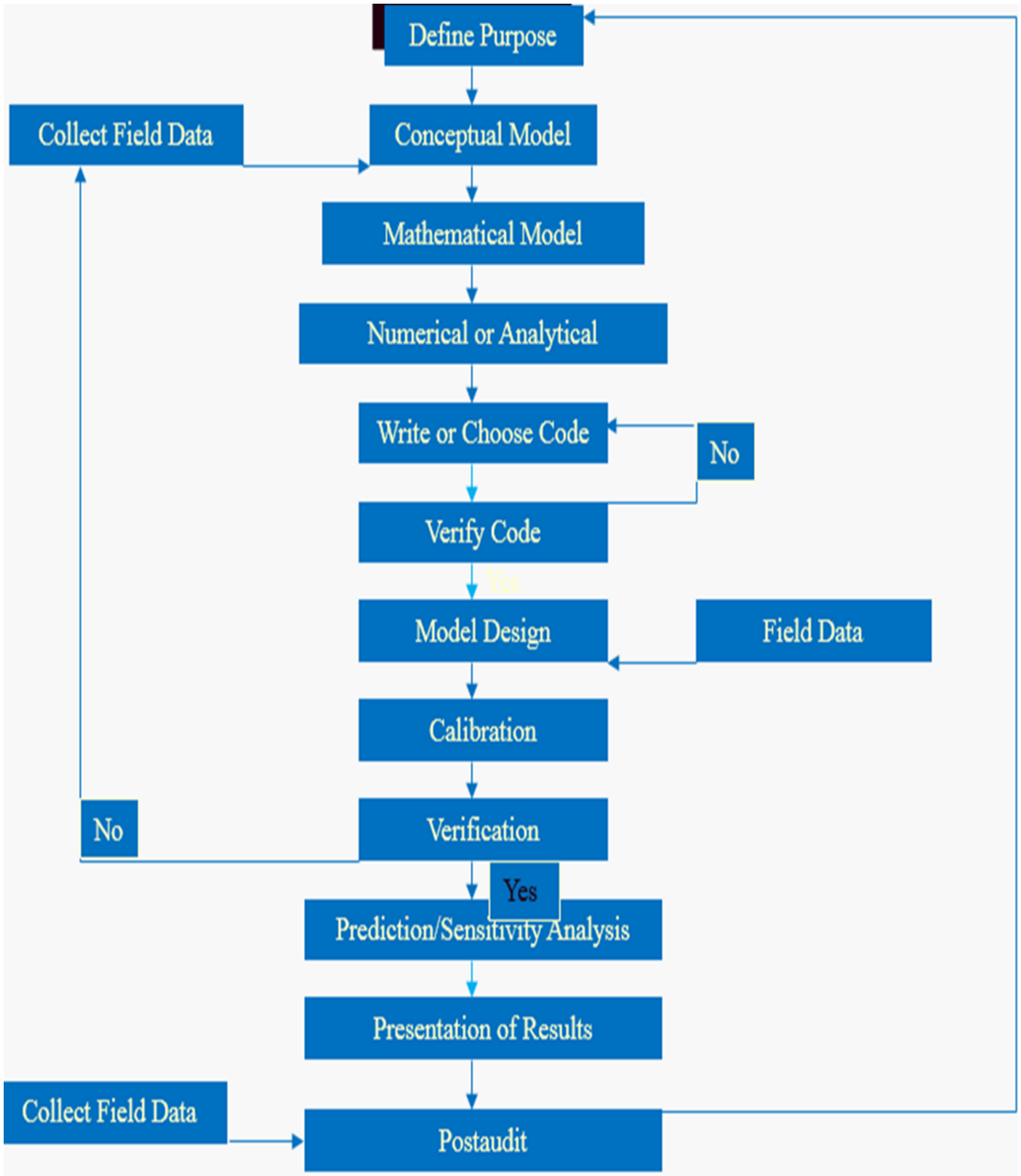


Figure 11: The different steps in hydrological model application (Anderson and Woessner 1992)

3.2.1 Analytical Methods

Analytical methods are those that can provide exact solutions to the equations that describe very simple flow or transport conditions and are usually employed when exact solutions for a number of problems can be obtain. Analytical element models give exact solutions of equations that describes sources and sinks and other parameters that are solved together using the superposition principle. They can be used in linear problems and regions of simple or regular geometry. Analytical solutions are not applicable in nonlinear problems with regions of irregular geometry, only a few anaylytical solutions exist which are usually approximations. Analytical methods can usually give good and exact solutions but it may require several assumptions to simplify the problem; something that might not be possible for complicated problems in some cases. In groundwater modeling; the application of analytical models is limited as many of its physical phenomena such as coupled fluid flow and solute transport in porous media are governed by complex nonlinear partial differential equations. Analytical models are generally incapable of solving such complex problems of nonlinear partial differential equations. Hence, the wide use of numerical models which are generally capable of giving appropiate approximated solutions. In simple terms, the flexibility and use of the analytical modeling is limited due to simplified assumptions of homogeneity, isotropy, simple geometry, simple initial conditions.

3.2.2 Numerical Models

Numerical models provide approximate solutions to equations that describe very complex conditions of groundwater. They use approximations to solve differential equations describing groundwater flow or solute transport and can solve more complex equations that describe groundwater flow and solute transport. The equations solved by numerical models generally describe multi-dimensional groundwater flow, solute transport and chemical reactions. Partial differential equations or a system of several partial differential equations together with initial and boundary conditions gives the complete description of transport in porous media in mathematical model. Numerical models are mostly used to obtain the solutions of these systems and are most suited in the simulation of complex two- or three-dimensional groundwater-flow and solute-transport problems. They have been applied in more complex groundwater problems simulations including steady-state or transient groundwater flow or solute transport, assess regional- or local-scale flow or transport, and estimate fluxes at simple or complex hydrogeological boundaries. Numerical models use approximations to solve problems which require that the model domain and time to be discretized. Discretization is done through the model domain been represented by a network of grid cells or elements, and simulation duration been represented by a series of time steps. (Anderson and Woessner, 1992) showed that numerical solutions are much more versatile and with the widespread availability of computers, they are easier to use than some of the more complex analytical solution.

The availability and use of input data is the most important factor in achieving accuracy in numerical models. Therefore, accuracy of numerical models is highly dependent on the accuracy of model input data, space size and time discretization and numerical method used to solve the model equations. It is important to note that the size of discretization steps corresponds to possibility of error; the greater the size of the discretization steps, the greater possible error. During a sensitivity analysis, calibrated values for hydraulic conductivity, storage parameters, recharge, and boundary conditions are systematically changed within a previously established plausible range. Numerical models have been used in several simulations of practical applications in groundwater resources.

There are two main types of numerical models; which are the finite difference and the finite element method. These two methods are the most popular methods that have been applied in the field of coupled fluid flow and solute transport in porous media. Finite difference and finite element methods are both very similar and in certain problems have been shown to be considered as two representations of the same model. However, in terms of flexibility, finite element method is somewhat more flexible than the standard form of finite difference method (Bear and Verruijt, 1987). Several numerical methods can be used to solve complex nonlinear partial differential equations Figure 12. The various numerical solution techniques used in groundwater models can be distinguished three different techniques: Finite Difference Method, Finite Element Method, and Analytical Element Method. They all possess their own advantages and disadvantages with respect to availability, costs, user friendliness, applicability, and required knowledge of the user. The two main techniques which are finite difference method and finite element method are discussed the following sections.

3.2.3 Finite Difference Method

Finite-difference methods are numerical methods for approximating the solutions to differential equations using finite difference equations to approximate derivatives which relies on discretizing a function on a grid. These are mathematical expression methods that can be used to solve the solute transport equation, either using backward, forward or central differencing. Finite difference method is the first and oldest method used in numerical modeling (Southwell, 1940; Forsythe and Wasow, 1960; Fox, 1962; Kantorovich and Krylov 1964). In this method, the partial derivatives appearing in the basic differences of the dependent and an independent variable is replaced by the differential quotient. Finite difference method is popularly used in the simulation of large systems since it is conceptually straightforward and the fundamental concepts are simply understood. Also, finite difference method is easy to understand and program, and fewer input data are needed to construct a finite difference grid. It is most suitable for problems with simple or regular geometry such as isotropic and homogenous aquifer with regular boundary. With these simple and regular geometry, the finite difference has a good accuracy level. However, it becomes complicated and inefficient when the problem is nonlinear with irregular domain such as anisotropic and heterogeneous aquifer with irregular boundary (Istok, 1989). An example of a model using finite difference method is the MODFLOW.

3.2.4 Finite Element Method

Finite element method is the second developed numerical method which is very powerful and is better at the approximation of irregular shaped boundaries compared to the standard finite difference. This method has become a powerful numerical tool for the solution of a wide range of engineering problems and has been found to be useful in every field of engineering analysis (Klaus, 1996). It was first used to solve groundwater flow and solute transport problems in the early 1970's (Istok, 1989) and it has ever since gained a wide acceptance in the field of fluid flow and solute transport modeling.

This method can produce near optimal approximate solutions to the partial differential equations of a certain problem. This is done through the subdivision of the problem domain into several elements with small regions or a complex region defining a continuum is discretized into simple geometric shapes called finite elements. The material properties and governing relationships are considered over these elements and expressed in terms of unknown values at element nodes. In this way, the finite element method treats each element separately and then assembles equations for all elements into global matrix equation. The solutions of these equations give the approximate behavior of the continuum (Chandrupatla and Belegundu, 1991).

Basic principle of the finite element method is to produce a set of algebraic equations, written on each finite element which are then collected together using a procedure called assembly to form the global matrix statement. Approximate values of the dependent variables are then determined via solution of this matrix statement using any linear algebra technique (Baker and Pepper, 1991). The steps that formulate a finite element model of solute transport problems are embodied in the developed finite element model. Steps of finite element analysis can be summarized as follows (Cheung et al., 1996):

1. Discretization of the problem domain into several sub-regions known as finite elements.

2. Selection of node and element interpolation functions.

3. Evaluation of individual element properties.

4. Formation of elements stiffness matrices.

5. Assembly of element matrices to form the global matrix.

6. Definition of the physical constraints (boundary and initial conditions).

7. Formulation of the global unknown vector.

8. Solution of system of equations for the unknown nodal variables.

9. Finally, computation of further parameters such as, hydrostatic head, fluid density, velocity, dispersion coefficients and other physically meaningful quantities from the computed nodal variables and element properties.

Finite element method requires more input data and more complicated compared to finite difference method. However, it has become very popular due its accuracy and ability to solve more complex systems and more advantageous as presented by (Daryl, 2002). Some of these advantages include its ability to handle irregular and curved geometric boundaries, variable spacing of the nodes, variable size of the elements, unlimited numbers and kinds of boundary conditions, anisotropic and heterogeneous materials, nonlinear behavior and dynamic effects etc. It is easier to adjust the size of individual elements as well as the location of boundaries with the finite element method, making it easier to test the effect of nodal spacing on the solution. Finite elements are also able to handle internal boundaries such as fault zones and simulate point sources and sinks, seepage faces, and moving water tables better than finite differences. Examples of finite element models are SUTRA, FEFLOW etc.

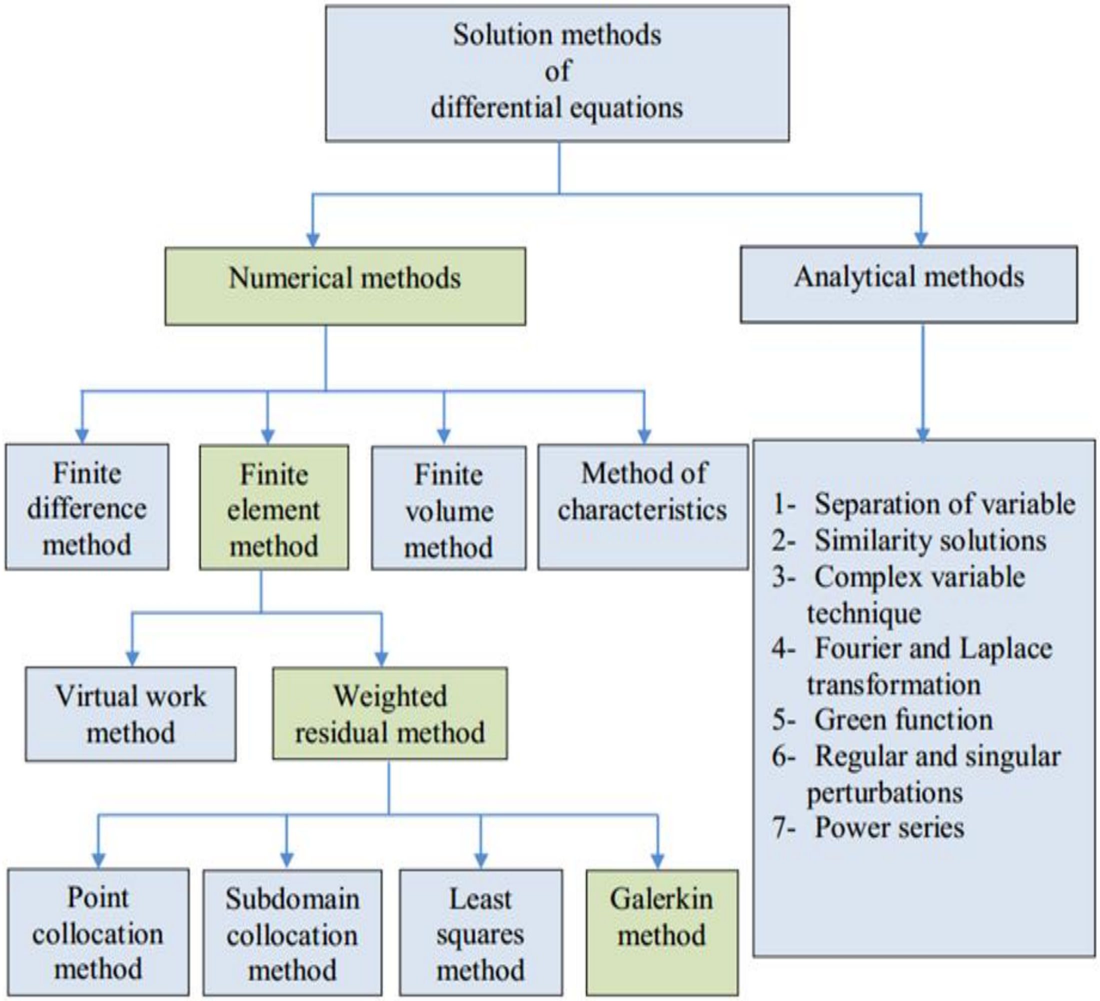


Figure 12**:** Summary of the solution methods for differential equations (Hany Farhat 2010)

3.3 Description of FEFLOW Model

FEFLOW is a software use for groundwater and porous media modelling which is capable of simulating multitude of processes involving fluid flow, groundwater-age, contaminant and heat transport in saturated and unsaturated porous media. FEFLOW is described as finite element subsurface FLOW system; a modular 3D finite element groundwater flow model. The model has a range of capabilities and it is an efficient tool in groundwater modelling; it contains pre- and post-processing functionality and an efficient simulation engine. Model includes a public programming interface for user code, it is user-friendly in the spatial discretization of irregular boundaries, coarse discretization, and can be adjusted to match the geometry, better control on numerical errors with a graphical interface that provides easy access to the extensive modelling options. The model's unique feature of not been a graphical front end for a separately developed simulation kernel but a completely integrated system from simulation engine to graphical user interface gives it an edge over other models. Also, its elements can be oriented along flow eliminating numerical dispersion transverse to flow.

FEFLOW model is a verified simulation code developed by DHI-WASY GmbH, the German branch of the DHI group which has a wide range of expertise in groundwater hydrology, surface water hydrology and geographic information systems. The model has since been used by leading research institutes, universities, consulting firms and government organizations all over the world. Its scope of application ranges from simple local-scale to complex large-scale simulations. It has become a standard in groundwater modelling over the last 35 years due to its efficient user interface and unmatched range of functionality.

3.3.1 FEFLOW Groundwater Modelling System

FEFLOW Version 6.2 released in 2013 is an interactive finite element simulation system for three-dimensional (3D) or two-dimensional (2D) model. 3D or 2D can be applied in either horizontal or aquifer-averaged, vertical or axi-symmetric, transient or steady-state, fluid density-coupled or linear, flow and mass, flow and heat or completely coupled thermohaline transport processes in subsurface water resources. Major computed results include hydraulic heads, flow patterns and solute concentrations (mass) of a contaminant or temperature distributions, since they are time depended with respect to different locations in the simulated area.

Advantages of FEFLOW

- The model is a completely integrated package from simulation engine to user interface.
- It maximizes productivity and limit the time and effort spent for model setup, simulation runs and results evaluation.
- Flexible meshing strategies and the option to include time-varying geometries allow for an accurate spatial representation of the geology.
- The reliability of model results is increase with FePEST, a tool for model calibration, uncertainty quantification and sensitivity analysis.
- The model allows the development of our own plug-ins as it is designed to handle plug-ins for extended functionality or for automating workflows.
- FEFLOW includes a license for WGEO, an excellent tool for quick and easy georeferencing and processing of spatially related raster data.
- Worldwide expert user support with high-level software training from THE ACADEMY by DHI.

Typical FEFLOW Applications

FEFLOW is applicable for a multitude of groundwater, porous media and heat transport projects from local to regional scale. It is the ideal software for:

- regional groundwater management
- groundwater management in construction and tunneling
- capture zone and risk assessment via groundwater-age calculation
- mine water management
- simulation of open-pit progress
- seawater intrusion
- seepage through dams and levees
- land use and climate change scenarios
- groundwater remediation and natural attenuation
- geothermal energy (deep and near surface, both open-loop and closed-loop systems)
- groundwater-surface water interaction
- simulation of industrial porous media

3.3.2 FEFLOW Basic Model Equation

The simulation system FEFLOW models the flow, mass transport and heat transport processes as combined or separable phenomena for saturated or partially saturated/unsaturated porous media. Numerical model which is used in this study is based on the finite element approach method. This involved the development of a finite element model for saturated/unsaturated fluid flow and solute transport. Basic equation for the simulation of three-dimensional flow and solute transport are as follows (Diersch 2002):

$$S_o \frac{\partial h}{\partial t} + \frac{\partial q_i^f}{\partial x_i} = Q_p + Q_{EB}\ (C, T) \qquad \} \text{ 3-1}$$

$$\frac{\partial}{\partial t}(\varepsilon RC) + \frac{\partial}{\partial x_i}\left(q_i^f C - D_{ij}\frac{\partial C}{\partial x_j}\right) + \varepsilon R\vartheta C = Q_C$$ Divergence form

} 3.2

$$\varepsilon R_d \frac{\partial C}{\partial t} + q_i^f \frac{\partial C}{\partial x_i} - \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) + (\varepsilon R\vartheta + Q_p)C = Q_C$$ Convective form

Where,

h = hydraulic head;

q_i^f = Darcy velocity vector of fluid;

C = concentration of chemical component;

T = temperature

S_O = specific storage coefficient (compressibility);

Q_{EB} = term of extended Boussinesq approximation,

R = retardation factor;

R_d = derivative term of retardation;

D_{ij} = tensor of hydrodynamic dispersion;

ϑ = decay rate;

ε = porosity;

Q_x = source/sink function of fluid(x=p), of contaminant mass (x=C) and heat(x=T);

The relationships of retardation R and Rd, respectively, can be summarized for the different adsorption laws as follows:

Henry isotherm:

$$R = 1 + \frac{(1-\varepsilon)}{\varepsilon}k$$

} 3.3

$$R_d = 1 + \frac{(1-\varepsilon)}{\varepsilon} k$$

Freundlich isotherm:

$$R = 1 + \frac{(1-\varepsilon)}{\varepsilon} b_1 C^{b_2 - 1}$$

} 3.4

$$R = 1 + \frac{(1-\varepsilon)}{\varepsilon} b_1 b_2 C^{b_2 - 1}$$

Langmuir isotherm:

$$R = 1 + \frac{(1-\varepsilon)}{\varepsilon} \frac{k_1}{1 + k_2 C}$$

} 3.5

$$R_d = 1 + \frac{(1-\varepsilon)}{\varepsilon} \frac{k_1}{(1 + k_2 C)^2}$$

Where,

k = Henry sorptivity coefficient;

b_1, b_2 = Freundlich sorption coefficient and exponent, respectively;

k_1, k_2 = Langmuir sorption coefficients.

Henry isotherm with a retardation factor of $R = 1 + \frac{(1-\varepsilon)}{\varepsilon} k$ is often expressed by distribution coefficient K_d in the form[7] $R = 1 + \frac{(1-\varepsilon)}{\varepsilon} p^s K_d$ with $K_d = \frac{k}{p^s}$, where p^s is the density of solid. An alternative definition of the distribution coefficient can sometimes be found as $R = 1 + \frac{p^b K_d}{\varepsilon}$, where $p^b = (1 - \varepsilon)p^s$ is the bulk density of the porous media (mass dry media per total volume). The chosen option in the model was Henry isotherm shown in Figure 13.

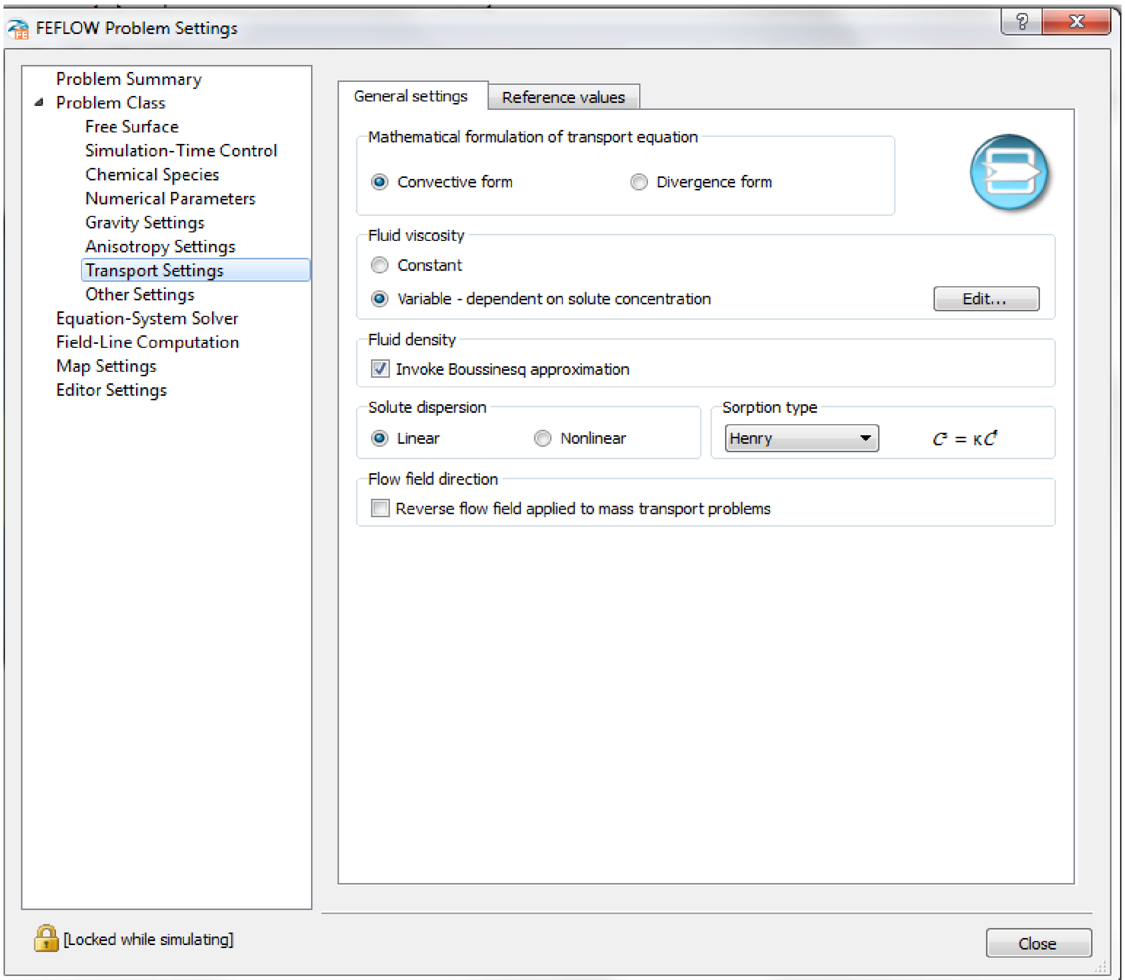


Figure 13: FEFLOW Problem Settings for Transport model

3.3.3 FEFLOW Model Parameters

Physical properties of the study area are applied to the finite-element model through the respective parameters found in the data panel. Parameters are organized in the following main branches in the tree view:

• Geometry

• Process Variables

• Boundary Conditions

• Material Properties

• Auxiliary Data

• User Data

• Discrete Features

The following steps were considered for easy modelling method;

- **Design super-elements:** Background maps created from ArcMap GIS model were loaded and activated. This allowed the possibility of setting different boundary conditions and material parameters as needed.
- **Generate Finite Element Mesh:** The design of different super-elements allows the possibility to vary the mesh density.
- **Assign problem attribute data:** FEFLOW offers many ways to import and assign data to the model including as POW files or manual entry. Parameter not specified and impermeable borders are set as defaults in the model.
- **Problem Class Settings**: The problem class setting involves the use of the right application for different stage of the simulation. Simulations are specified has steady state, transient, mass or heat transport. Also, the type of aquifer whether confined or unconfined.

- **Run simulator:** The simulator is run after all necessary and required setting of the model has been done.
- **Final results:** The postprocessor offers many options for the output of results.

At different stages of the simulation presents the use of process variables from the data panel. Steady state and flow model simulations considers geometry, process variables, boundary conditions, and materials properties. Transport models adds mass transport properties which account for inflow concentration and mass concentration.

3.4 Governing Equations in Groundwater Modeling

Groundwater models describe the groundwater flow and transport processes using mathematical equations based on certain simplifying assumptions. Governing equations in groundwater modeling are important in translating conceptualize physical systems into mathematical terms. The results of this mathematical terms are the familiar groundwater flow and transport equations. It is necessary to understand these equations and their associated boundary and initial conditions to be able to formulate a modelling problem. Prediction of the movement of solute and energy transport in aquifers is a process that can be divided into three sections: the fluid flow, energy transport and solute transport processes. Flow distribution can be obtained once the fluid pressure distribution through the domain is determined. There are different mechanisms through which solute transport in groundwater occurs which includes: advection, diffusion, dispersion, adsorption, chemical reaction, and biological degradation. The transport of energy in the groundwater and solid matrix of the aquifer includes the changes in temperature due to the change in conduction, convection and latent heat transfer (AL Najjar, 2006).

Solving of groundwater problems involving water quality requires an additional equation to solve for the concentration of the chemical species. Resultant model for this is solute transport model which can be applied in various water quality issues such as seawater intrusion, landfills, waste injections, radioactive waste storage, holding ponds, groundwater pollutions etc. Groundwater modeling studies are conducted for the most part based on deterministic models, which are based on precise description of cause-and-effect or input-response relationships or stochastic models reflecting the probabilistic nature of a groundwater system. Darcy law explained in Figure 14 plus water balance equation with head as the depended variable, boundary conditions as well as initial conditions in the case of transient problems are the basics for groundwater flow equations. In principle, groundwater moves from areas of higher potential to areas of lower pressure or elevation. Direction of groundwater flow is therefore depended on topography of the land surface from higher to lower. In the subsurface, groundwater flow is in complex 3D patterns. Darcy law in three dimensions can be regarded to one dimension. A completely saturated aquifer with a fluid density ρ is represented in equation 3.6.

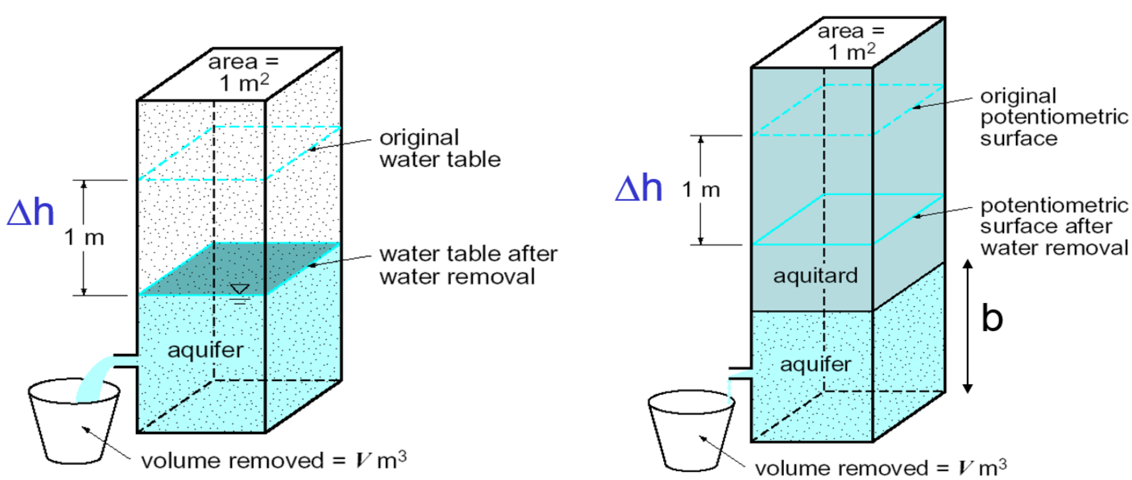


Figure 14: Explanation of Darcy law (Hornberger et al. 1998)

$$S = \frac{V}{A\Delta h}$$

$$S = S_s b$$

Unconfined aquifer | Confined aquifer
Specific yield | Storativity

Mass influx (M/T) – Mass out flux (M/T) = rate of change of mass (M/T)

$$\rho q_x - \frac{\partial(\rho q_x)}{\partial x}\frac{\Delta x}{2}\Big]\Delta y\,\Delta z - \Big[\rho q_x + \frac{\partial(\rho q_x)}{\partial x}\frac{\Delta x}{2}\Big]\Delta y\,\Delta z = -\frac{\partial(\rho q_x)}{\partial x}\,\Delta V \qquad (3.6)$$

Mass in   Mass out   Mass flux

3.4.1 Governing Equations for Flow Models

Governing equations of groundwater flow are found based on law of mass balance plus Darcy law, which eventually yield groundwater flow equations. It is the equation that provides the solution to the resultant equation of the groundwater flow problem formulated in terms of its hydraulic head. Governing flow equation for three-dimensional saturated flow in saturated porous media is:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - Q = S_s\frac{\partial h}{\partial t} \qquad (3.7)$$

Where,

K_{xx},$K_{yy,}$ K_{zz} = hydraulic conductivity along the x,y,z axes which are assumed to be parallel to the major axes of hydraulic conductivity;

h = piezometric head;

Q = volumetric flux per unit volume representing source/sink terms;

S_s = specific storage coefficient [L^{-1}] defined as the volume of water released from storage per unit change in head per unit volume of porous material.

The following equations shows the basic equations of different groundwater flow conditions under confine and unconfined aquifer as wells as the general 3D Darcy's law.

2D confined: $\frac{\partial}{\partial x}\left(T_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y\frac{\partial h}{\partial y}\right)= S\frac{\partial h}{\partial t}-R$ (3.8)

2D unconfined: $\frac{\partial}{\partial x}\left(hK_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(hK_y\frac{\partial h}{\partial y}\right)= S\frac{\partial h}{\partial t}-R$ (3.9)

Where; S is storativity [dimensionless], and b is aquifer thickness [L]

S = S_s b & T = K b

Generalized equations in 3D (Darcy Law)

$$q_x = -K_{xx}\frac{\partial h}{\partial x}-K_{xy}\frac{\partial h}{\partial y}-K_{xz}\frac{\partial h}{\partial z} \qquad (3.10)$$

$$q_y = -K_{yx}\frac{\partial h}{\partial x}-K_{yy}\frac{\partial h}{\partial y}-K_{yz}\frac{\partial h}{\partial z} \qquad (3.11)$$

$$q_z = -K_{zx}\frac{\partial h}{\partial x}-K_{zy}\frac{\partial h}{\partial y}-K_{zz}\frac{\partial h}{\partial z} \qquad (3.12)$$

Equations 3.10, 3.11 and 3.12 represent the groundwater flow discharge in three directions in x, y and z respectively.

3.4.2 Governing Equations for Solute Transport in Groundwater

Solute transport equation is used in solving problems and involving miscible fluid by solving both the groundwater flow and solute transport equation. Governing equations of the dispersion zone and flow pattern in coastal aquifers subjected to seawater intrusion under the unsteady state conditions are (Bear and Veruijt, 1987):

1. General Darcy equation for groundwater flow.

$$q = -\frac{k}{\mu}(\nabla p + \rho g \nabla z) \quad (3.13)$$

Where q is the specific discharge vector (LT^{-1}), k is the permeability tensor (L^2), μ is the dynamic viscosity ($ML^{-1}\ T^{-1}$), p is pressure ($ML^{-1}\ T^2$), ρ is the fluid density (ML^{-3}), g is the gravitational acceleration (LT^2) and z is a space coordinate (L), Substitution of

$$\psi = \frac{p}{\rho_f g} + z, \qquad k = \frac{k\rho_f g}{\mu} \quad and \qquad \rho_r = \frac{p}{\rho_f} - 1$$

into the general Darcy equation, then equation (3.13) can be written as:

$$q = -K(\nabla\psi + p_r \nabla z) \quad (3.14)$$

where K is the hydraulic conductivity tensor (LT^{-1}), ψ is the equivalent hydraulic head (L), and p_r is the relative density (dimensionless).

2. Basic fluid continuity equation or the mass balance equation for the fluid which can be written as:

$$\frac{\partial n\rho}{\partial t} = -\nabla\rho q + R\rho^* + P\rho \quad (3.15)$$

Where, n is the effective porosity (dimensionless), R and P are the recharge and pumping rates per unit volume of aquifer medium, respectively (T^{-1}), and ρ* is the density of the recharge water (ML^3).

3. Hydrodynamic dispersion equation or the mass balance equation for the salt ions can be written as:

$$\frac{\partial nc}{\partial t} = -\nabla(qc - nD\nabla C) + RC^* - PC \quad (3.16)$$

where C is the solute concentration in mg/l. In the above equation, the effect of adsorption on dispersion process and solute transport is neglected.

4. A constitutive equation relating fluid density to solute concentration, which is expressed as:

$$\rho = \rho_f + a(c - c_f) \tag{3.17}$$

Where c_f is the freshwater concentration (ML^{-3}), and a is known constant (dimensionless) which can be calculated as:

$$a = \frac{\rho_s - \rho_f}{C_s - C_f} \tag{3.18}$$

where ρ_s is the seawater density (ML^{-3}), and C_s is the seawater concentration (ML^{-3}). A linear relationship for the density and concentration is assumed in equation (3.17). (Baxter and Wallace 1916) developed an empirical relation which relates the salt concentration to fluid density as:

$$\rho = \rho_f + (1 - E)\rho_s \tag{3.19}$$

Where E is a constant (dimensionless) and has a value of 0.3 for concentrations as high as seawater. The observation of these four equations (3.14, 3.15, 3.16 and 3.17) reveals four unknowns (ψ, V, C and ρ) in these equations. These equations can however be combined into two nonlinear partial differential equation in only two variables, which are the hydraulic head ψ and the concentration C. The effects of density are included in models used to simulate flow containing high TDS or higher or lower temperatures. And as such density-depended flow of miscible fluids problems requires the solving of three models-flow, solute transport and heat transport. Models used to simulate density-dependent flow requires an initial pressure and density distribution and these initial values are used to generate the first approximation of the flow field at the beginning of a time step. The results of these initial head values are then input into the transport models, which redistribute solute and/or temperature.

Chapter 4: Hydrogeological Conditions of the Study Area

4.1 Introduction

Groundwater is an important source of water supply in UAE representing about 51% of total water supply which is mostly use for irrigation (ICBA, 2010). The reduction in groundwater use could be linked to many factors including the increase in desalination capacity as well as increased restrictions in groundwater use. Groundwater is mainly used for agricultural development and as such agricultural activities depend on groundwater availability. Agricultural activities are most concentrated in the emirates of Ras Al Khimah and Fujairah. There has been an observed decreased of groundwater levels in these emirates due to low level of recharge from rainfall coupled with continuous pumping for farming activities. Furthermore, groundwater salinity levels have increased over the last decade mainly due to seawater intrusion and consequently farms have been abandoned. Figure 15 Shows land satellite image of Wadi Ham area including main features, it also highlights location of residential areas as well as major nearby areas which are directly or indirectly interlink with the study domain.

4.2 Geological Settings

Geology can be defined as the physical and chemical properties and distribution of local rocks, as well as prevailing tectonic conditions according to (Toth 1970). Geological characteristics highly affect the flow paths of groundwater, water will flow more readily through materials of higher permeability for a given hydraulic gradient. Gravel and sand mixtures have much higher permeability than silt and clay mixtures. Location map of the study area and geological map of the Emirate of Fujairah is shown in

Figure 15 and Figure 18 respectively. Figure 18 shows that the study area is dominated in its upper part by the Masafi Mountains and by alluvial plains in its lower part which is composed of recent Pleistocene Wadi gravels. This layer is underlain by the consolidated rocks of the Semail formation (Ophiolite sequence) with a mantle of fractured zones at some locations. Gravels of the wadi are poorly sorted and sub-rounded to sub-angular. The level of consolidation varies from recent un-cemented sandy gravel to the older well cemented and consolidated gravels. Clastics size ranges from silt grade to bounder sized material with a very high sand content. Gravels are typically composed of basic igneous clasts with other clasts of very well cemented sandstone and conglomerates according to (Entec 1996). The developed aquifer bottom and ground surface contours are shown in Figure 16 and Figure 17 respectively with the aquifer thickness found by the subtraction of aquifer bottom from surface elevation. Variation of gravel thickness from inland to coast of Wadi gravel varies from 15 to 100 m (Sherif, et al 2006).

There were several subsurface cross sections along different directions constructed to examine the geology of the aquifer as shown in Figure 19 with the location of respective wells in the study domain shown in Figure 23**.** Minimum thickness of the aquifer was found around the area of well number BHF-19 at upstream of Wadi Ham close to the mountain series. Maximum thickness is observed in well number BHF-14 which is very close to the coast of Oman Gulf. The cross-sectional depth of wadi gravels and sand along the wadi course varies from 45 m to 64 m**.** Thickness decreases with increasing distance from the shoreline, for example within 3 km it varies from 24 (BHF-7) to 73 m (BHF-12). This could be attributed to the regional dipping of Ophiolite series towards the Wadi channel. However, the gabbro and diorite of the Samail Ophiolite are encountered beneath the wadi gravels and which are likely to be confined in some places by the cemented units.

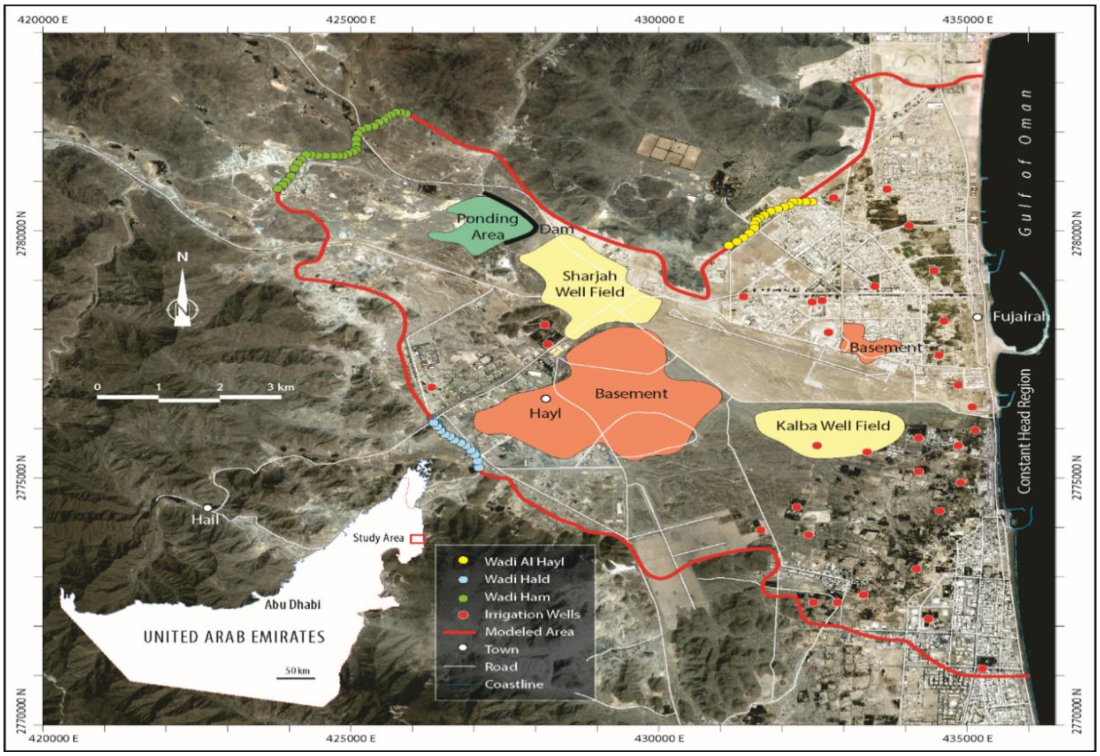


Figure 15: Land satellite image of Wadi Ham area including main features (Sherif et al 2013)

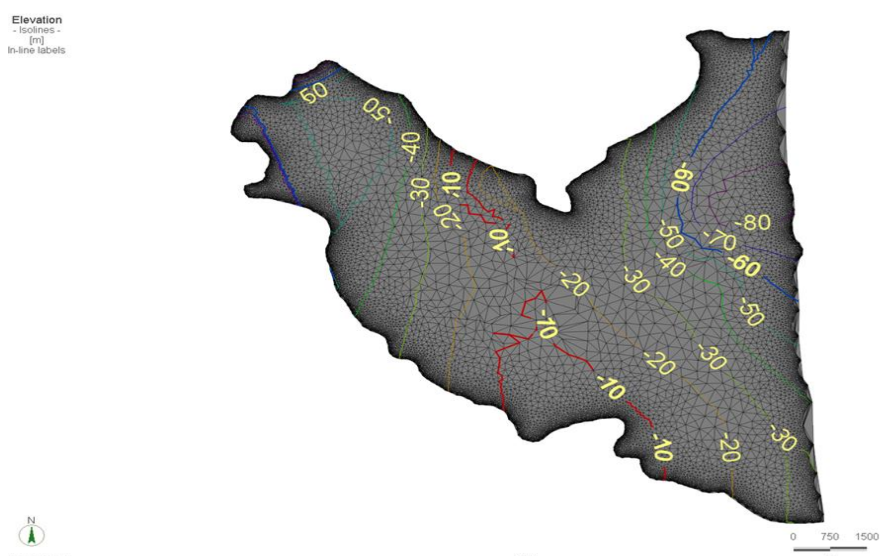


Figure 16: Contour of aquifer bottom (MSL)

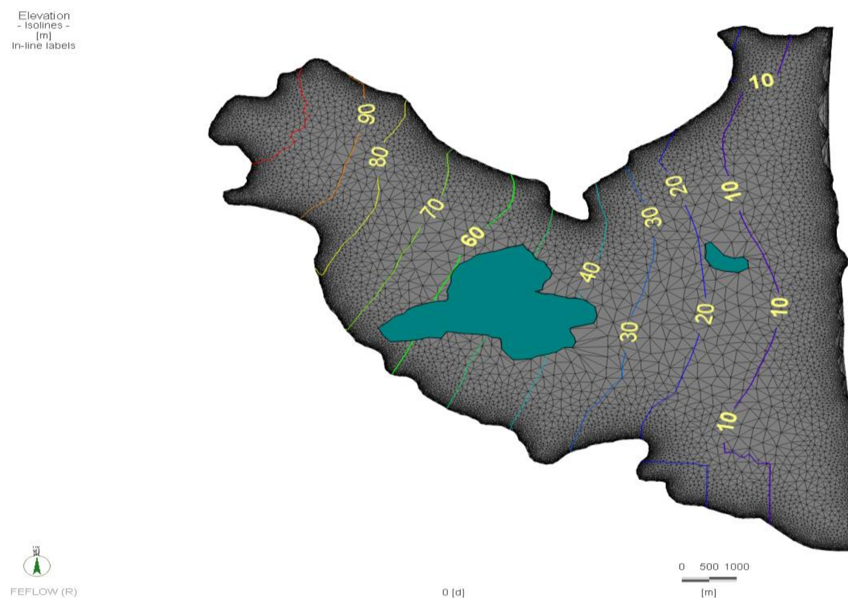


Figure 17: Ground-surface elevation (m) with referenced to (MSL)

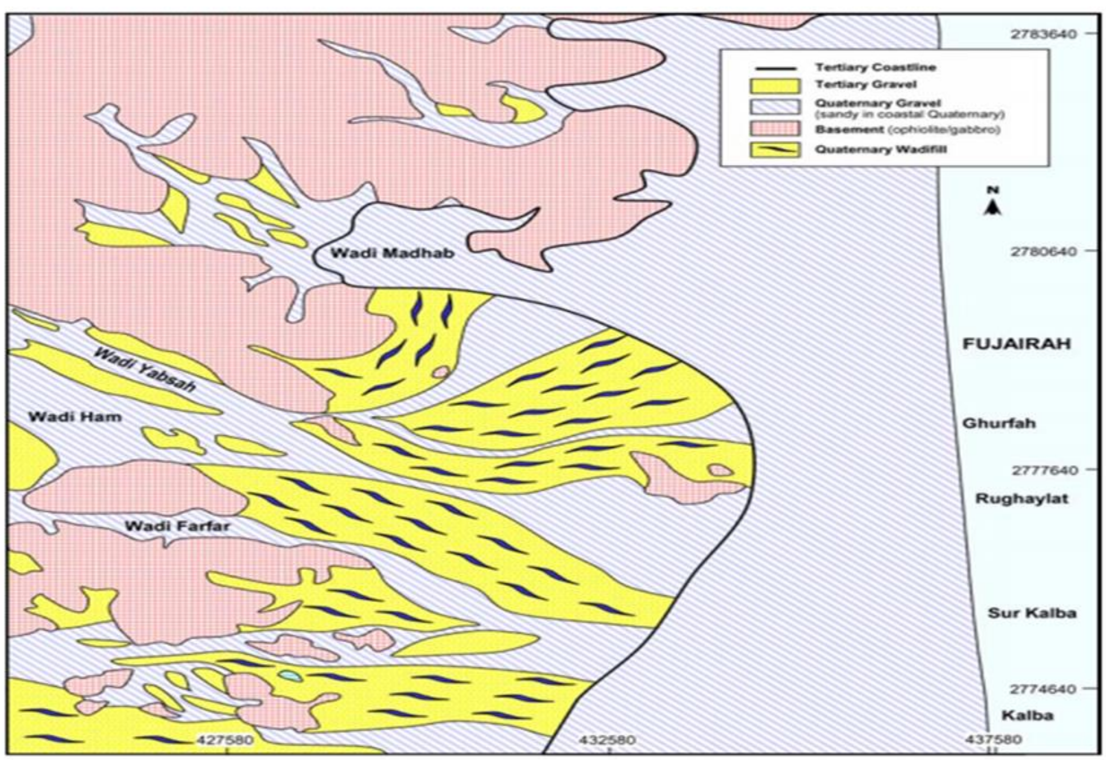


Figure 18: A sketch for the geological map of Fujairah (Geoconsult and Bin Ham, 1985)

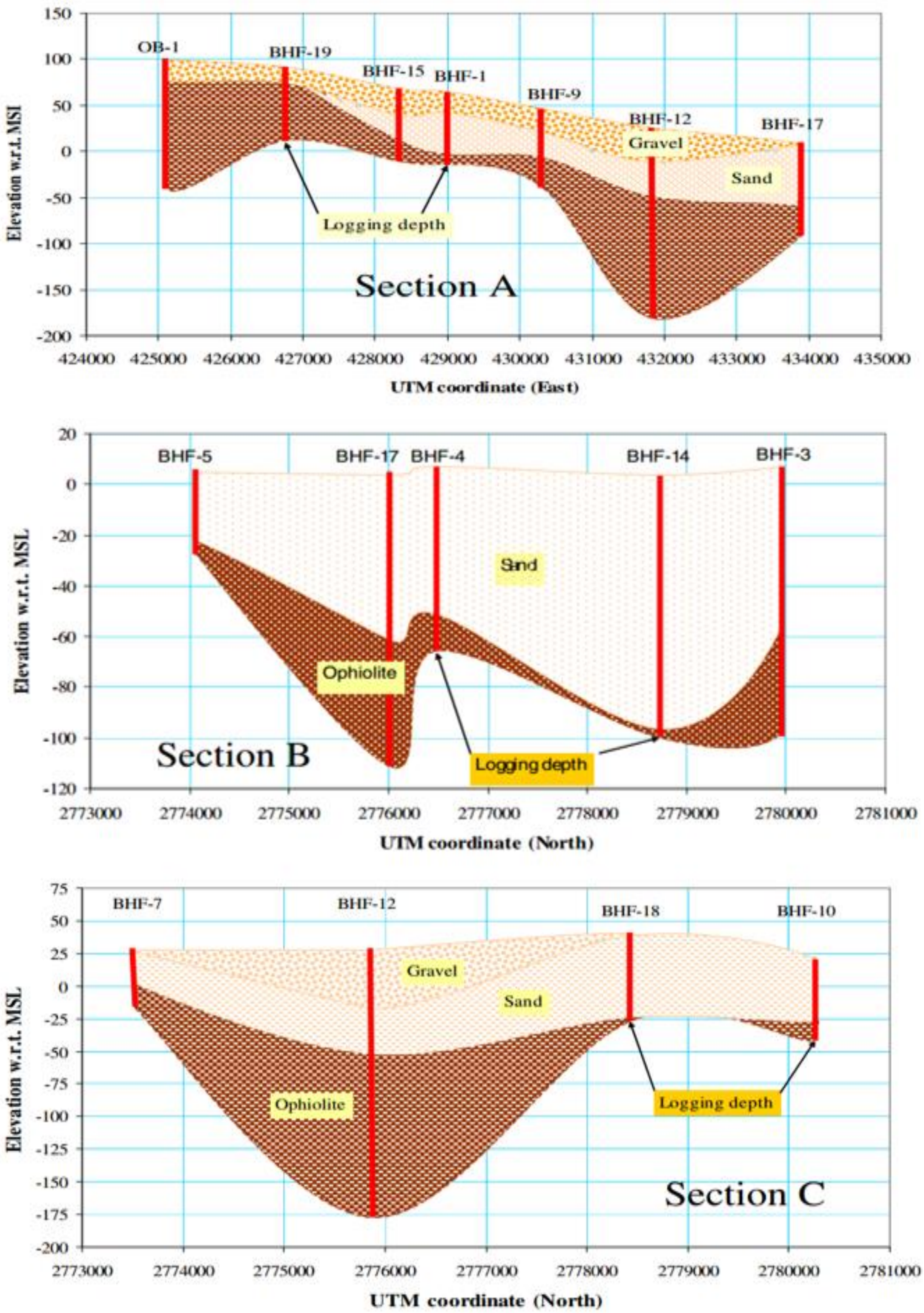


Figure 19: Several *g*eological cross-sections across Wadi Ham (Sherif, et al 2006)

4.3 Hydrological Parameters

There are two aquifers identified in the study area based on the interpretation of the available data. These two aquifers shown in Figure 20 are the Quaternary aquifer which is composed of wadi gravels constitute the main aquifer and the fractured Ophiolite which is of low groundwater potentiality. Characteristics of the gravel layer include high permeability and tends to be unconsolidated at the ground surface. The extent of consolidation ranges with depth from recent uncemented sandy gravel to the older well cemented consolidation gravel. (Electrowatt 1981) subdivided this gravel layer into recent gravels, being slightly silty sand gravel with some cobbles; young gravels, which are silty sandy gravels with many cobbles and boulders; and old gravels, which are silty sandy gravels with many cobbles and boulders which are weathered and cemented. Hydrogeological map of Wadi Ham is presented in Figure 20 which is also considered to be the conceptual model of the study area with the catchment area covering sand and gravel.

Hydraulic conductivity of the unconsolidated gravels tends to be high, typically from 6 to 17 m/day and in the range 0.086–0.86 m/day for the cemented lower layers (Electrowatt1981; ENTEC 1996). The unconsolidated gravels have a very primary porosity in comparison to the cemented gravels. (Electrowatt 1981; ESCWA 1997) found that the storage coefficients typically range from 0.1 to 0.3. The Wadi has about a width of 2.0 km, the saturated thickness varies between 10 and 40 m and the transmissivity ranges between 100 and 200 m^2/day. Saturated thickness varies between 50 and 100 m and the transmissivity value ranges between 1,000 and 10,000 m^2/day towards the shoreline. Range of hydraulic conductivity is from 2 to 250 m/day (IWACO 1986). (IWACO 1986) performed several short duration pumping tests which were analyzed by using Cooper & Jacob and Theis method, Transmissivity values estimated ranged from 8.3 to 6959 m^2/d. Table *3* shows the available data and results where transmissivity varies from 4.13 to 11,700 m^2/day by Cooper and Jacob method and from 3.83 to 9,120 m^2/day by Theis method. Hydraulic conductivity ranges from 4.73 to 203 m/day for the Theis method while it ranges from 3.16 to 745 m/day for the Cooper and Jacob method.

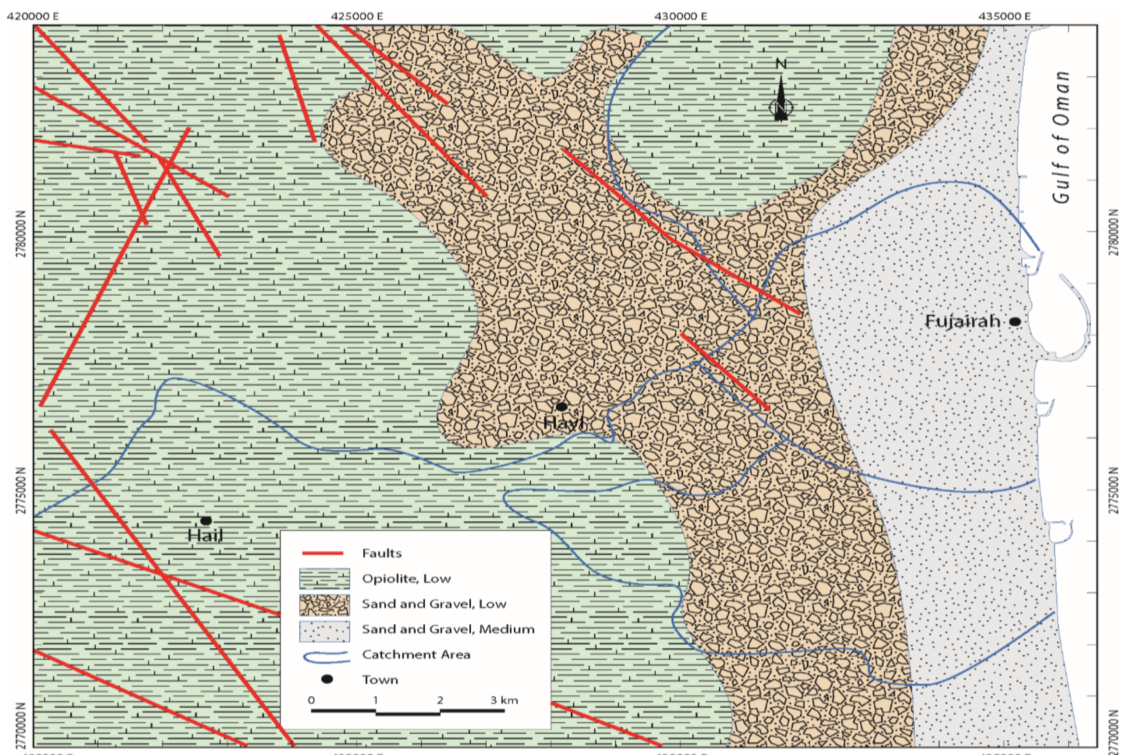


Figure 20: Hydrogeological map of Wadi Ham (Electrowatt 1981)

4.4 Groundwater Levels

Groundwater levels of observation wells in Wadi Ham area which were collected by the Ministry of Environment and Water Resources were used in this study. Table 6 shows the complete records of the groundwater level fluctuation of minimum and maximum values of water table from 1987 to 2003. There is a significant variation in the groundwater level in response to recharge events with the maximum groundwater levels observed in 1996; the year with highest recorded rainfall event. There is a constructed dam in the study area to enhance recharge into the aquifer. Groundwater level fluctuation reached a maximum of 51 m and was found in the observation well BHF-15, which is close to the dam site while the minimum level was recorded at observation well BHF-17A. Groundwater gradient in the plain area is very mild as compared to the gradient of groundwater within the Wadi valley close to the dam area. There is a decline in groundwater levels below mean sea levels at some locations. Figure 21 showed a general trend of groundwater levels decline in the observation wells located in Wadi Ham. The relationship between monthly rainfall and groundwater levels are plotted on the same figure which showed a clear relationship between rainfall events and groundwater levels.

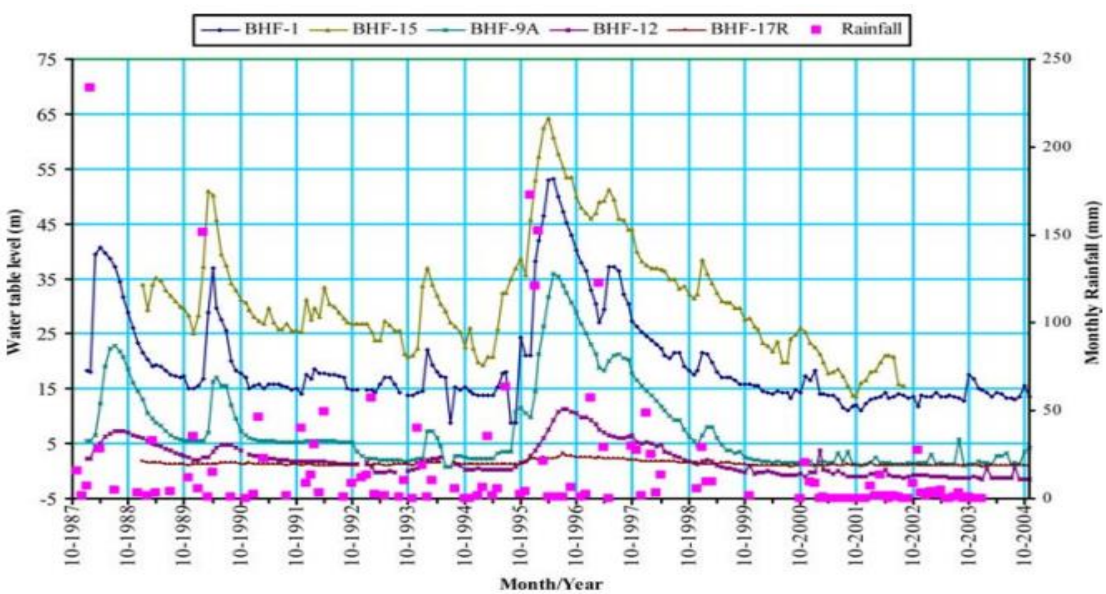


Figure 21: Groundwater levels in observation wells and rainfall events from 87-2004
(Sherif, et al 2006)

Table 3: Estimated aquifer parameters (Sherif, et al 2006)

Borehole	**UTM coordinate**		**Transmissivity (m^2/day)**	**Transmissivity (m^2/day)**		**Hydraulic conductivity (m/day)**		**Storativity**
	Northing	Easting	IWACO	C&J method	Theis method	Theis method	C&J method	
BHF-1	2,779,163	429,211	30	101	148	7.76	11.4	0.00161
BHF-4A	2,776,995	433,773	8,630	11,700	9,120	203	259	2.01E-15
BHF-12	2,776,432	431,865	1,340	947	789	15.5	18.6	0.00239
BHF-3A	2,779,800	432,900	3,450	6,246	744	14	118	6.21E-08
BHF-5	2,773,400	432,950	4,347	8,940	1,260	105	745	1.33E-20
BHF-10	2,780,250	431,800	1,230	480	258	6.79	12.6	0.00197
BHF-11	2,781,000	430,450	386	101	151	4.73	3.16	0.00666
BHF-13	2,774,900	427,800	8.5	4.13	3.83	25.6	27.5	0.0101
BHF-14	2,778,750	433,900	2,882	4,750	3,630	39.4	51.6	3.03E-07
HAM-OB1	2,780,166	427,151	-	0.49	0.51	0.0058	0.0056	0.00128

4.5 Geophysical Studies

Seawater intrusion in Wadi Ham was delineated by (M. Sherif et al 2006) using a 2D earth resistivity survey by monitoring existing wells to measure the horizontal and vertical variations water salinity. Four 2D-resistivity profiles were run (Profiles 1-4**;** Figure 22 which are numbered from I to IV respectively in Figure 23) to assess the groundwater quality and seawater intrusion in the coastal aquifer of Wadi Ham. They obtain an empirical relationship between the inferred earth resistivity and the amount of total dissolved solids from the vertical electrical soundings and chemical analyses of the collected water. This relationship was used along with the true resistivity sections resulting from the inversion of 2D resistivity data to identify three zones of water-bearing formations (fresh, brackish, and salt-water zones). Groundwater quality in Wadi Ham varies from freshwater, slightly brackish water in the northwestern and northeastern parts of the area to saline water in the coastal zone (Sherif et al. 2006a). This paper provided an insightful information for our current study as it identified the transition (dispersion) zone between the freshwater body and the seawater body in the coastal area of Wadi Ham. Figure 22 showed that salinity of groundwater due to seawater intrusion increases mainly eastward toward the shore line and to a lesser extent southward. This increase could be because of the excessive irrigation in Kalba area or due to its bay which is around 10 km away from the study area (Sherif et al. 2006a).

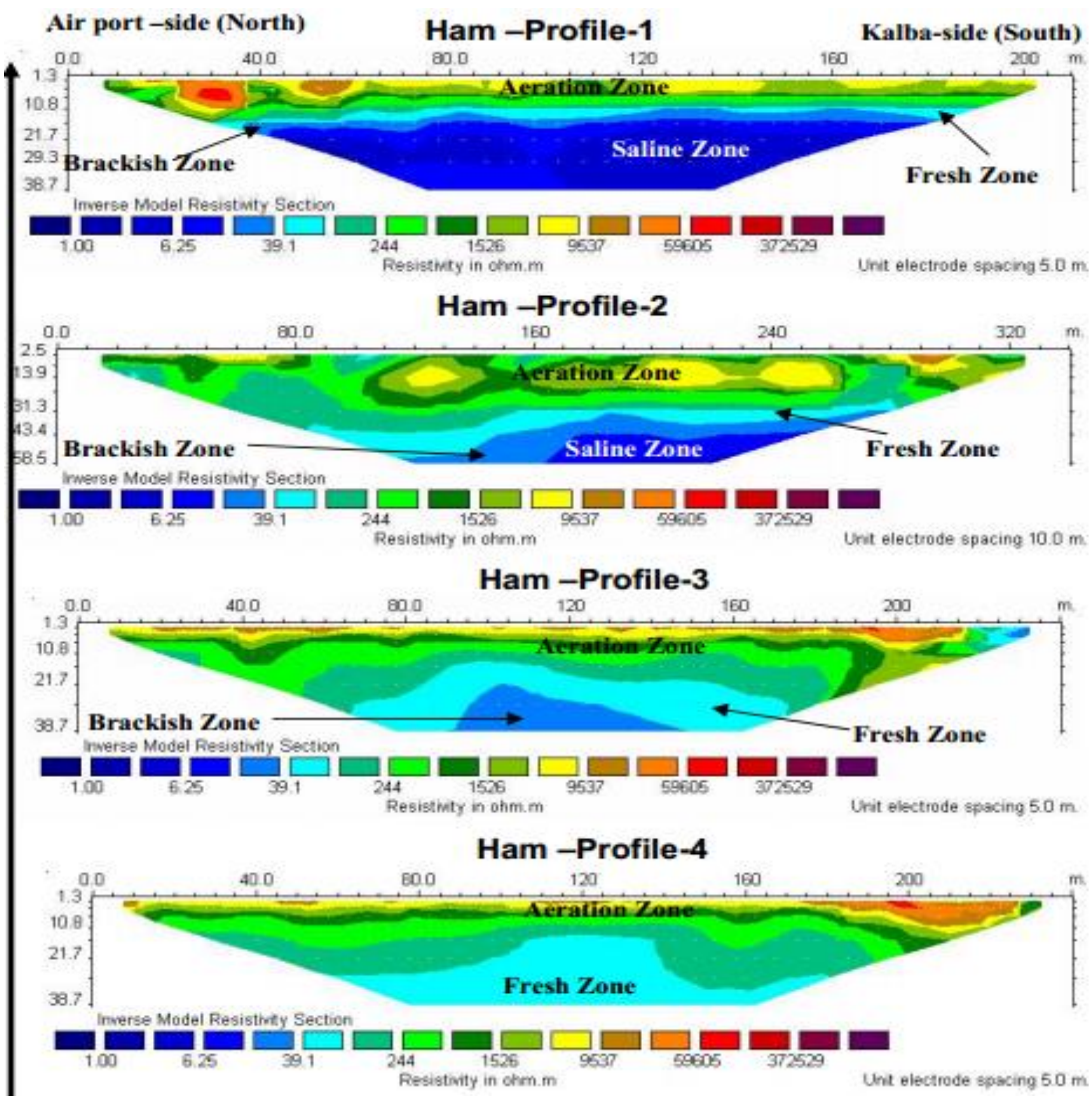


Figure 22: Combined diagrams of four true resistivity sections (increasing SI eastward) (Sherif et al., 2013)

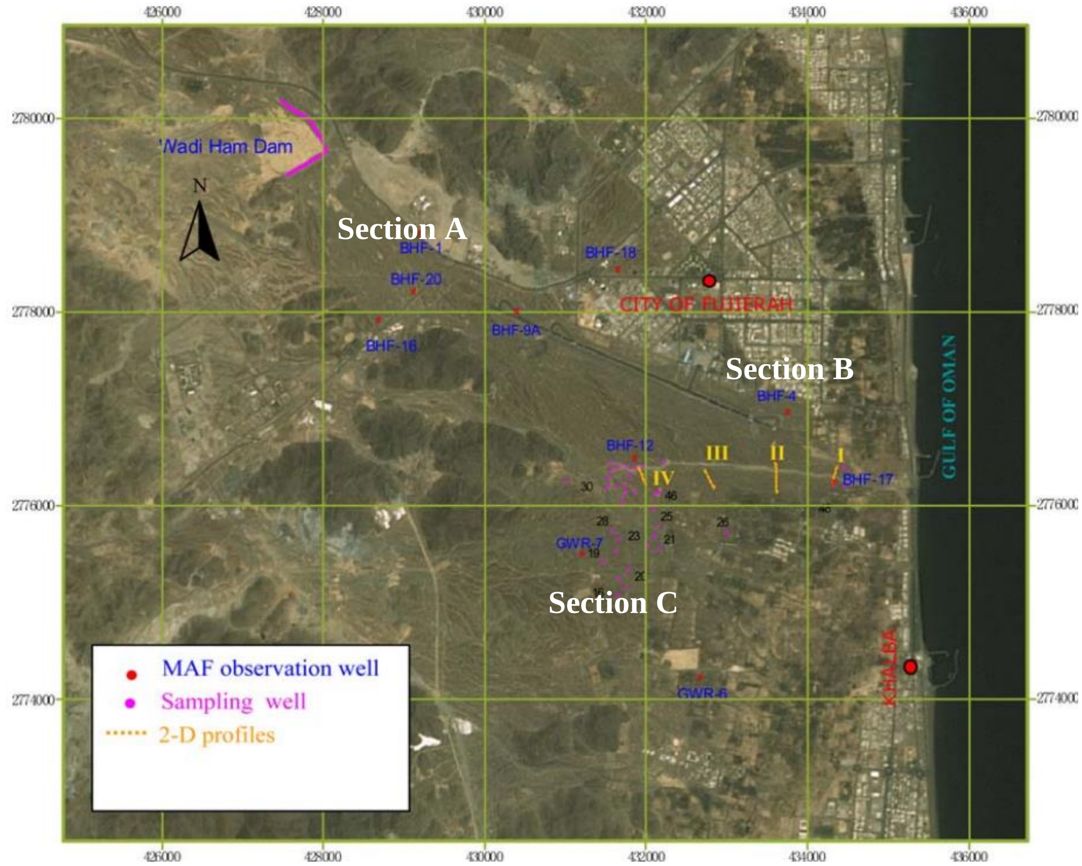


Figure 23: Location map of the study area including monitoring and production wells and locations of 2D profiles (Sherif, et al 2006a)

4.6 Groundwater Quality in Wadi Ham

The reviewed papers (Sherif et al 2006a, 2006, 2012, 2014a, 2015) showed a deteriorating groundwater quality in the coastal aquifer of Wadi Ham. Previous studies conducted in the study area evaluated and assessed the presence of different chemical elements such as Na, Ca, Mg, Cl etc. Measured total dissolved solids (TDS) was used as an indicator of the mineralized character of the groundwater in the study area. The used of groundwater is depended on the level of TDS with typical values of 500 mg/l or less considered satisfactory for domestic use. Higher values of TDS values ranging from 1000 mg/l and above are generally unfit for for potable use, values from 1000 to 10,000 mg/l are considered as brackish and could be useful for agricultural purposes. Higher TDS values are sometimes assoiciated with the presence of other characteristics such as hardness. There are other properties useful in determining groundwater character include hardness, specific conductance and pH.

The study and charasterization of the origin of seawater in the coastal aquifer is an important step in understanding the major source of saline water in the aquifer. Table 4 shows the geochemical criteria for distinguishing seawater origin. (Sherif et al 2006) studied the geochemical criteria for distinguishing salt water origin in the year 2000. They estimated the ratios of Na and Cl, Ca and Mg, and Ca and HCO3+SO4 as shown in Table 5. As per table 5; the ratio of Ca and HCO3+SO4 for BHF-16, GWR-5 and GWR-6 exceeds 1 which suggest the existence of seawater. Well number BHF-16 is 8 km away from the coast of Gulf of Oman while well number GWR-5 and GWR-6 are close to the coast which suggest that the presence of salt water could be as a result of seawater intrusion. Also, the ratio of Ca and Mg in BHF-16 and GWR-5 exceeds 1 suggesting the existence of seawater. Variation of EC values with water level from 1989-95 is also presented in Figure 24. Electrical conductivity (EC) of water is an indirect measure of its dissolved constituents which is expressed in terms of the specific electrical conductivity defined as the reciprocal of electrical resistance in ohm (Ω) in relation to a water cube of edge length 1 cm at 20 ^{0}C. Figure 24 showed that the trend of EC values has a relationship with the groundwater water level variation with a rise in groundwater level corresponding to a decline in Ec values. These results showed high presence of seawater in the study area which suggest an indication of seawater intrusion.

Table 4: Geochemical criteria for distinguishing seawater origin (Sherif et al 2006)

Measurement	Criteria
Chloride, Cl	A time-series of Cl concentrations can record the early evolution of relatively rapid salinization processes.
Cl/Br ratios	Cl/Br = 297 : Seawater. Cl/Br < 297 : Hypersaline Brines. Cl/Br > 1000 : Evaporite Dissolution products. Cl/Br up to 800: Anthropogenic Sources (e.g. sewage).
Na/Cl ratios (Malor)	Na/Cl =0.86 : Seawater. Na/Cl < 0.86 : Seawater intrusion. Na/Cl > 1.0 : Anthropogenic Sources (e.g. sewage)
Ca/Mg	Ca/Mg > 1.0 : Seawater intrusion.
Ca/(HCO_3+SO_4)	Ca/ (HCO_3+SO_4) > 1.0: Seawater intrusion.

Table 5: Geochemical criteria for distinguishing seawater origin for the year 2000 (Sherif et al 2006)

SI. No.	Well No.	Na/Cl	Ca/Mg	Ca/(HCO_3+SO_4)
1	BHF-19	0.45	0.2	0.32
2	BHF-15	0.53	0.4	0.56
3	BHF-16	0.74	10.0	1.40
4	BHF-9B	0.85	1.5	0.81
5	BHF-6	0.22	0.5	1.90
6	BHF-5	0.58	71.0	4.50
7	BHF-4	0.82	0.3	0.23
8	BHF-22	0.79	0.1	1.17
9	BHF-23	1.04	0.6	0.35

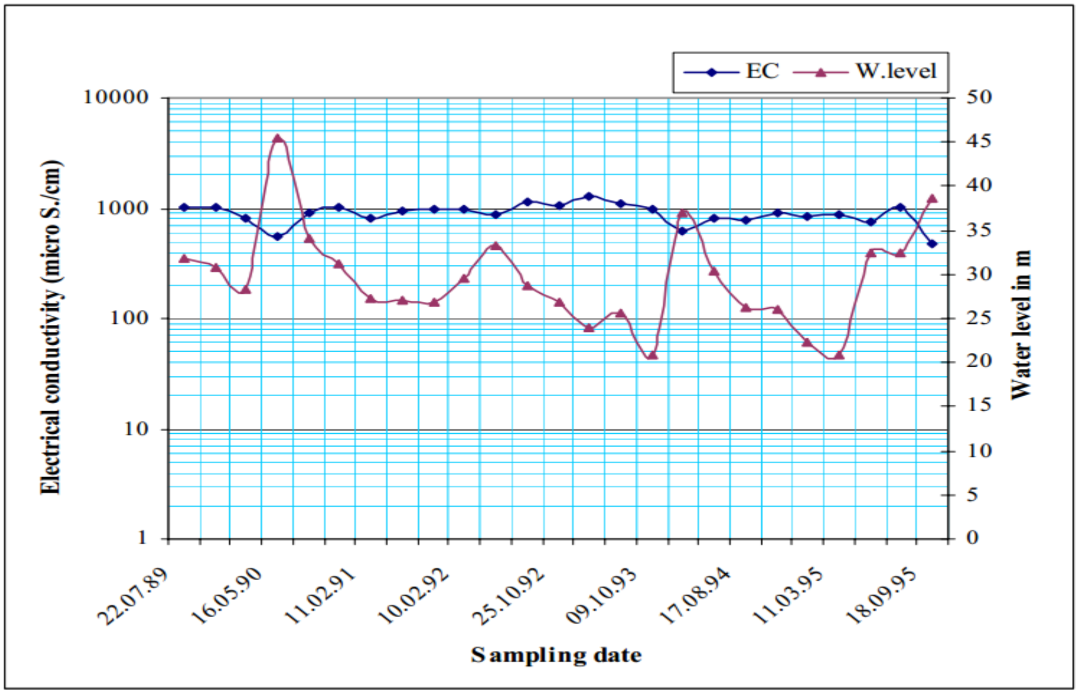


Figure 24: Variation of Ec values with water level from 1989-95 (Sherif et al 2006)

Chapter 5: Flow Model Development, Calibration and Simulations

5.1 Data Collection and Preparation

The study area of Wadi Ham due to its importance for groundwater resources in UAE has attracted lots investigations both from academic and government agencies for the management of its groundwater resources (Sherif et al 2006, 2012, 2014, 2015)**.** Publications of these investigations has generated a pool of data for our study and data was collected through an in-depth review of all publications related to the study area. These data included rainfall data, aquifer parameters, groundwater level, observation wells information, lithological information, hydrogeological information, geological maps. Table 6 presents the minimum and maximum values of water table from 1977 to 2003. From the table 6, maximum values of groundwater levels in May 1996 were taken as initial head that is because in that month and year presented the most measurements. In simple terms, the data used was adopted from previous studies done in the same study area; however, study approach and objective was different from all previous studies. This study investigated the mitigation of seawater intrusion by pumping brackish water from the intrusion zone; a different approach from previous studies. Average monthly rainfall data from the period of 2003 to 2014 was collected from the National Center of Meteorology and Seismology website of the Abu Dhabi Emirates, UAE shown in Figure 31. The images used were all taken from previous literature, these images were however digitized to suit our study objectives.

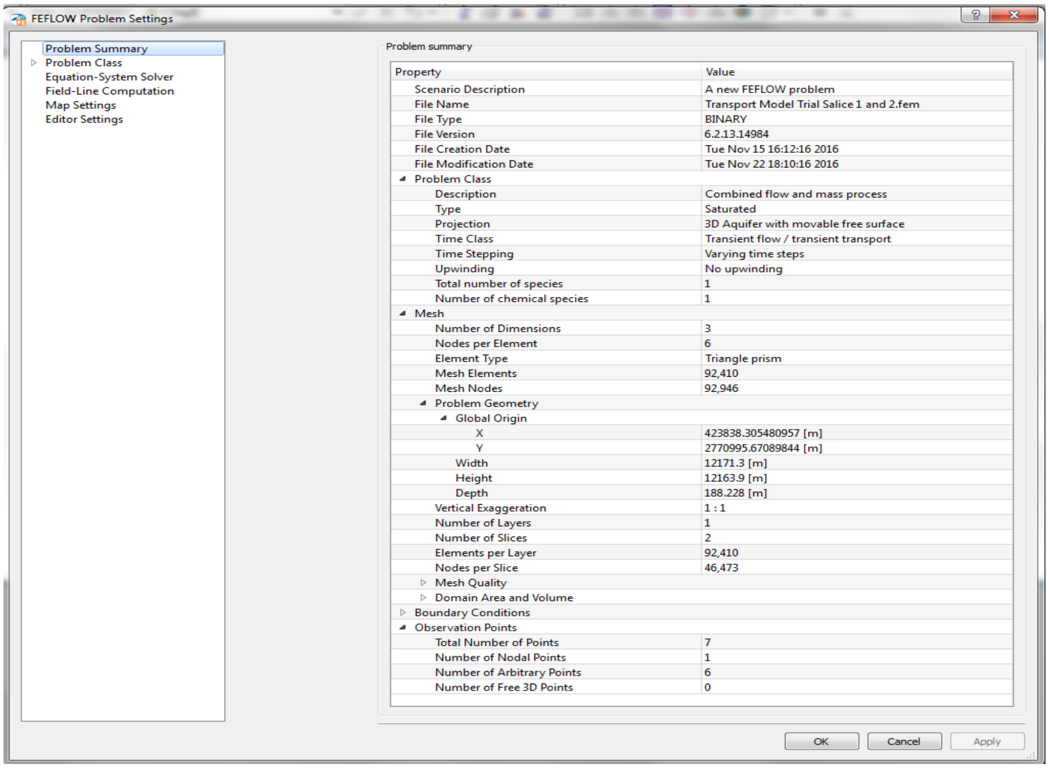
Table 6: Minimum and maximum values of water table (Sherif, et al 2006)

Obs. Well	**Period**	**Max. water Level**	**Table Month/yr**	**Min. water Level**	**Table Month/yr**	**Remark**
BHF-1	1987-2003	53.066	May-96	8.876	Jul-94	Active
BHF-4	1988-2003	5.805	Aug-96	2.585	37438	Active
BHF-4A	1990-2003	5.777	Aug-96	2.347	37438	Active
BHF-9A	1987-2003	35.789	May-96	0.728	Jun-94	Active
BHF-9B	1990-2003	35.59	May-96	3.02	37438	Active
BHF-12	1987-2003	11.329	Jul-96	-1.191	Aug-02	Active
BHF-15	1988-2002	64.106	Apr-96	13.516	Oct-01	Abandoned
BHF-16	1988-2003	54.317	May-96	33.627	Sep-02	Active
BHF-18	1988-2000	12.364	Aug-96	-0.256	Nov-89	Abandoned
BHF-19	1995-2003	86.618	Mar-96	52.27	Oct-02	Active
BHF-20	1995-2002	53.969	May-96	21.559	Sep-02	Abandoned
BHF-17R	1988-2003	3.153	Jul-96	0.823	Aug-00	Active
BHF-17A	1989-2003	3.897	Jun-97	1.477	Sep-99	Active
GWR-6	1977-2002	5.015	Sep-96	-3.955	Dec-84	Active
GWR-5	1977-2002	3.602	May-96	-0.168	Dec-80	Dry/Abandoned

We prepared the data supporting files using excel, notepad, and ArcMap GIS model as an interface. These data were converted into shape files using ArcMap GIS model for use in the FEFLOW model. The study area images taken from literature were first copied then converted into jpef image and uploaded to ArcMap for digitizing. During the digitizing process, we adopted the same boundary as the previous literature (Sherif et al. 2013 Figure 15). The study domain and boundary conditions were as such prepared as shape files. Shape files for the outcrop boundary, ponding boundary, and well field boundary was each created separately. We used contour maps to digitize aquifer bottom and location of the geological sections and the groundwater surface elevation with referenced to mean sea level.

5.2 Model Development

The created shape files from the ArcMap GIS software were uploaded in the open window of the FEFLOW model. A grid design of 1500 elements was generated through the Grid Builder option and outside boundaries of the study area were refine since it attracts more interaction. The total number of elements, nodes and other parameters used are presented in Figure 25. Files such as observation wells, hydraulic conductivity, outcrop boundary, ponding area, specific yield, initial head conditions, and hydraulic head files were loaded into the model. The model domain was created into two slices that represent topography and bottom of the aquifer. Parameters such as initial hydraulic head, hydraulic conductivity, porosity, elevation etc. were applied on the top slice while an impermeable condition was adopted in the bottom slice. FEFLOW model was set as steady state during the steady state calibration which is done by using the problem setting dialog. This setting would be changed accordingly to transient for the flow model and then to mass for the solute transport model. After the initial set up, the model would be run for the steady state calibration.



Property	Value
Scenario Description	A new FEFLOW problem
File Name	Transport Model Trial Salice 1 and 2.fem
File Type	BINARY
File Version	6.2.13.14984
File Creation Date	Tue Nov 15 16:12:16 2016
File Modification Date	Tue Nov 22 18:10:16 2016
Problem Class	
Description	Combined flow and mass process
Type	Saturated
Projection	3D Aquifer with movable free surface
Time Class	Transient flow / transient transport
Time Stepping	Varying time steps
Upwinding	No upwinding
Total number of species	1
Number of chemical species	1
Mesh	
Number of Dimensions	3
Nodes per Element	6
Element Type	Triangle prism
Mesh Elements	92,410
Mesh Nodes	92,946
Problem Geometry	
Global Origin	
X	423838.305480957 [m]
Y	2770995.67089844 [m]
Width	12171.3 [m]
Height	12163.9 [m]
Depth	188.228 [m]
Vertical Exaggeration	1 : 1
Number of Layers	1
Number of Slices	2
Elements per Layer	92,410
Nodes per Slice	46,473
Mesh Quality	
Domain Area and Volume	
Boundary Conditions	
Observation Points	
Total Number of Points	7
Number of Nodal Points	1
Number of Arbitrary Points	6
Number of Free 3D Points	0

Figure 25: FEFLOW problem setting

5.3 Model Conceptualization and Boundary Conditions

The study area is represented in a conceptual model for modeling the system. There are two aquifers identified in the study area, one main aquifer was suggested encompassing the recent Pleistocene wadi gravels. This main aquifer is regarded as an unconfined aquifer, and in some locations capped by a thin semi-porous layer with a relatively high vertical conductivity (Sherif, et al 2014). The bottom layer is overlying a thick impervious layer of Ophiolitic sequence whose bottom is impermeable in nature. Therefore, a one layer model of wadi gravel and sand was considered (Sherif, et al 2014).

Maximum groundwater levels in Table 6 of May 1996 were considered as initial hydraulic head condition for the development of a steady state groundwater levels. The outside boundaries of the study domain were delineated and the boundary conditions adopted in this study were the same as those of (Sherif et al. 2013). Three inflow boundaries specified flux were assigned with different inflow rates while the remaining sides were assigned as no flow boundary due to the presence of physical boundaries as shown in Figure 27. The area occupied by the Gulf of Oman about 12.6 km of coastline in the model domain was considered as constant head boundary cells with a sea level head (0.0 m) for the entire steady state and flow modeling period. Figure 26 shows the Ophiolite outcrops covering an area of 6.56 km^2 which were specified as inactive or no flow areas and no flow boundary condition. In the study domain, the dam ponding area was delineated and marked. Total area of the ponding zone at the flood level is about 0.40 km^2 which has been built to improve groundwater recharge in the aquifer. A recharge polygon created accounted for recharge from rainfall during rainy days only and was applied to the entire domain except in outcrop areas where impermeable ophiolite formations were considered.

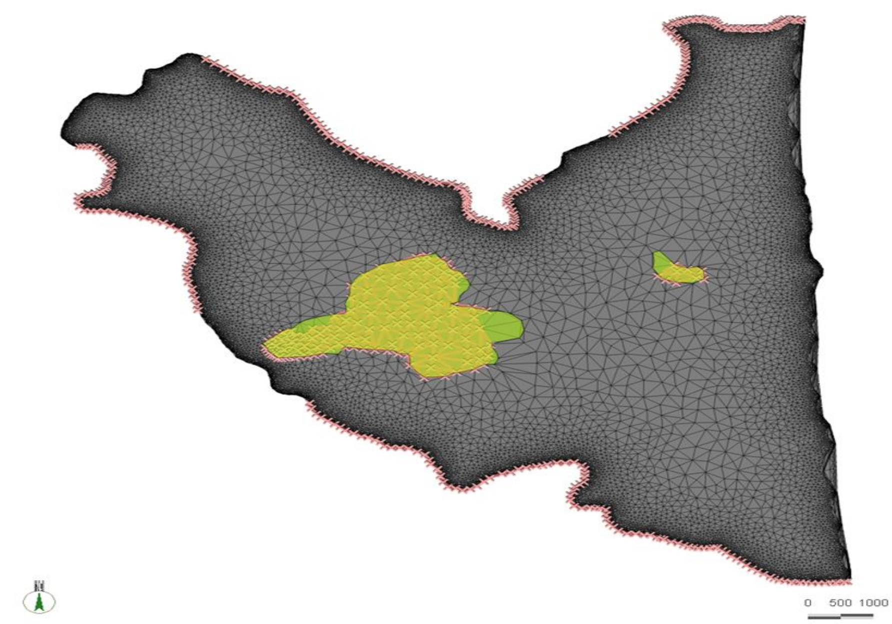


Figure 26: No flow boundary conditions and inactive outcrop

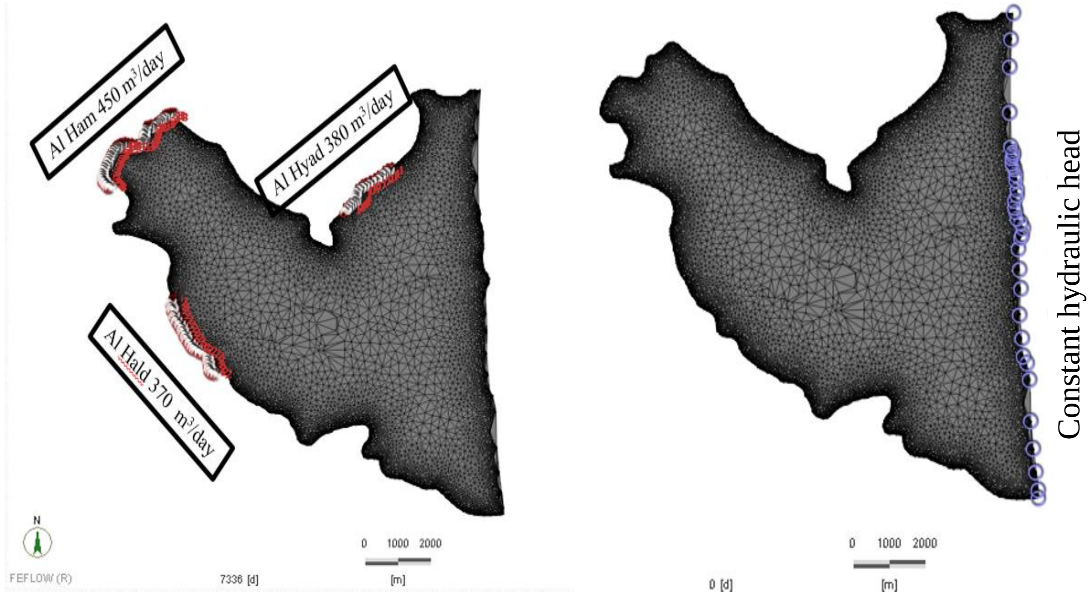


Figure 27: Inflow boundary conditions

5.4 Steady State Calibration

Calibration is the process in which model input parameters are adjusted, either manually or through formal mathematical procedures until a satisfactory matched is obtained between field and observed conditions. There are different model output variables considered during the calibration including hydraulic heads, flow rates, solute concentrations, or mass removal rates, depending on the objectives of the simulation.

Along the coastal boundary; a constant hydraulic head boundary of zero was taken. Steady state calibration was done by altering the hydraulic conductivity shown in Figure 29; and the range of alteration was kept within ±10% range. The initial hydraulic head was compared with the results of the model simulated hydraulic head. After a series of changes; we obtain an acceptable range of difference between the compared conditions as shown in Figure 30 in a scatter plot of computed hydraulic head vs observed hydraulic head.

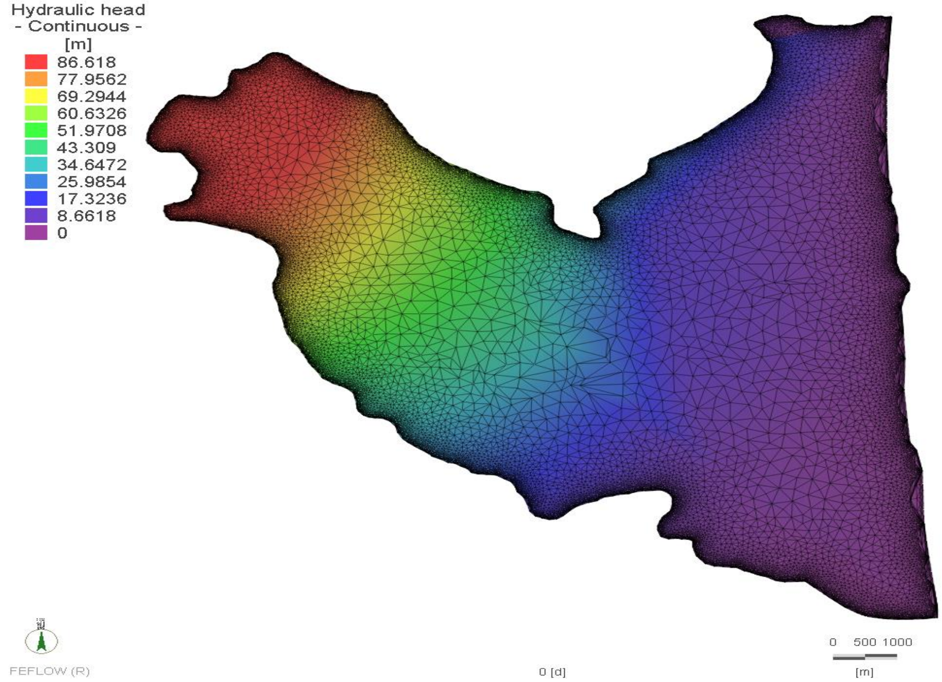


Figure 28: Initial hydraulic head condition of May 1996

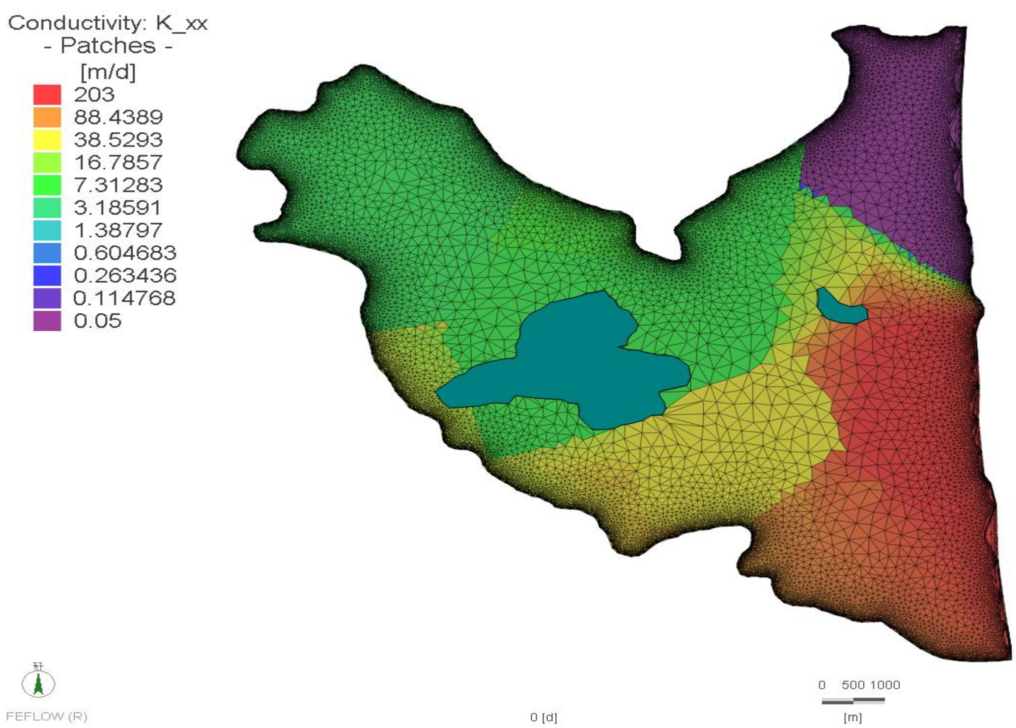


Figure 29: Observed hydraulic conductivity

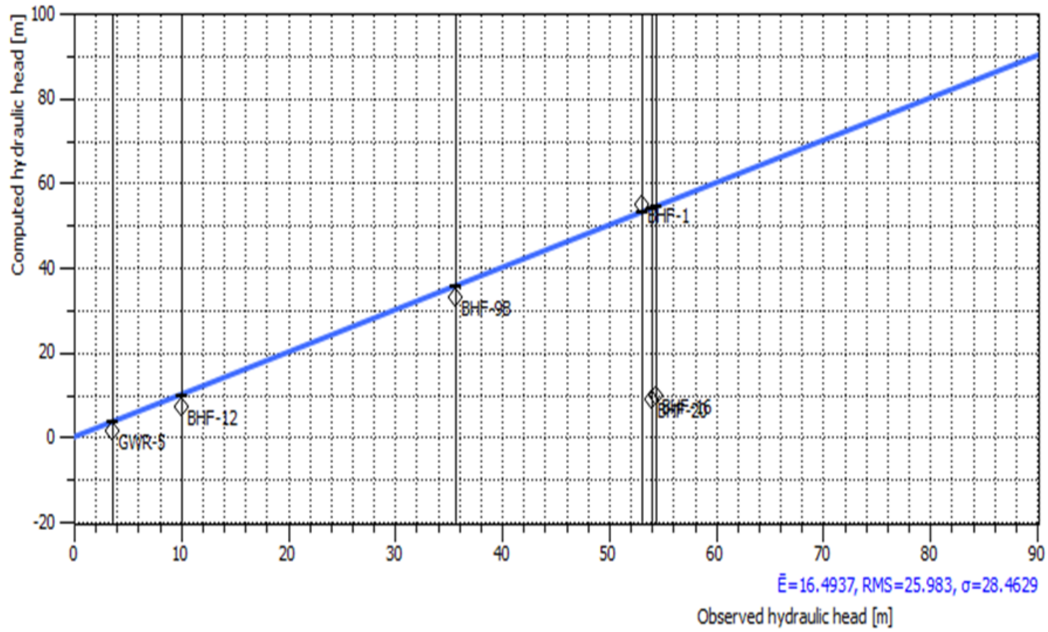


Figure 30: Scatter plot of observed vs computed hydraulic head (FEFLOW)

5.5 Flow Model Calibration and Simulations

The values of the hydrological condition of abstractions rates was varied during the process of calibration and verification. This is done to reduce the disparity between the model simulations and field data and essentially improve model accuracy. Groundwater models can be applied in predictive simulations such as to simulate possible future changes to hydraulic head or groundwater-flow rates because of future changes in stresses on the aquifer system. For more accurate predictive simulations, monitoring of hydraulic heads, hydraulic gradients, and groundwater-flow rates will be required to support predictive simulations using groundwater-flow models.

Flow model calibrated period was 7 years from May 1996 to 2003 and observed groundwater levels of the same period was used during calibration for comparison. Steady state calibrated aquifer parameter was reloaded for the aquifer matrix and observed groundwater data was used as initial hydraulic head for the flow model calibration. Flow model was calibrated by changing the rates of pumping at various well locations to match the observed groundwater levels. Final rates of inflow at the three main flux areas were also change accordingly as shown in Figure 27 with an inflow of 450 m^3/day, 380 m^3/day and 370 m^3/day respectively. A recharge factor of 20% of measured rainfall (mm/day) was assigned to all active cells on daily basis. The model was run after each set up and results of runs were saved as POW files and then open with excel to be compared with the available observed groundwater levels of the respective wells. This process was done for several runs and after a certain number of runs; an acceptable matched was obtained. Flow model calibrated results for well number BHF-12, BHF-9B and BHF-1 are presented in Figure 32 to Figure 34 respectively. Calibrated results of all three wells were used in the subsequent simulations for the flow model.

Station		Year السنة											
		2014	2013	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003
Abu Dhabi Airport	Rainfall	45.74	31.11	7.17	8.48	82.30	98.13	59.86	8.84	60.82	20.58	26.78	51.81
	Rainy days	26	20	22	15	19	30	15	21	23	25	14	21
Al - Ain Airport	Rainfall	64.88	81.32	12.46	24.73	9.72	115.07	36.85	68.52	95.33	33.96	33.07	79.92
	Rainy days	21	24	15	22	21	21	15	20	28	24	12	20
Dubai Airport	Rainfall	59.83	55.09	50.36	23.91	53.80	107.79	135.88	7.68	102.89	23.50	74.30	36.95
	Rainy days	19	18	16	19	18	31	25	15	27	26	17	27
Sharjah Airport	Rainfall	46.22	85.94	19.53	18.36	93.03	135.47	125.61	13.61	168.26	57.16	76.58	44.30
	Rainy days	23	23	19	21	24	32	27	20	32	32	15	35
Ajman Station	Rainfall	16.70	18	...	...	...	...	...	...	...	...	...	...
	Rainy days	5	5	...	...	...	...	...	...	...	...	...	...
Umm Al - Quwain Station	Rainfall	21.40	61.60	17.00	23.40	17.40	40.00	40.10	10.80	59.40	24.40	12.40	0.40
	Rainy days	9	13	5	9	3	9	8	14	18	11	8	1
Ras Al - Khaimah Airport	Rainfall	55.40	48.72	16.00	27.51	89.33	195.42	156.45	30.32	151.53	105.04	80.22	58.55
	Rainy days	16	16	7	12	10	28	23	13	28	17	14	18
Fujairah Airport	Rainfall	60.28	122.74	66.43	57.19	35.75	129.78	47.77	40.11	85.69	63.02	58.97	24.62
	Rainy days	20	26	16	23	17	28	18	23	28	29	26	28

Figure 31: Annual rainfall quantity and number of rainy days by Station (mm) 2003-2014 (NCMS)

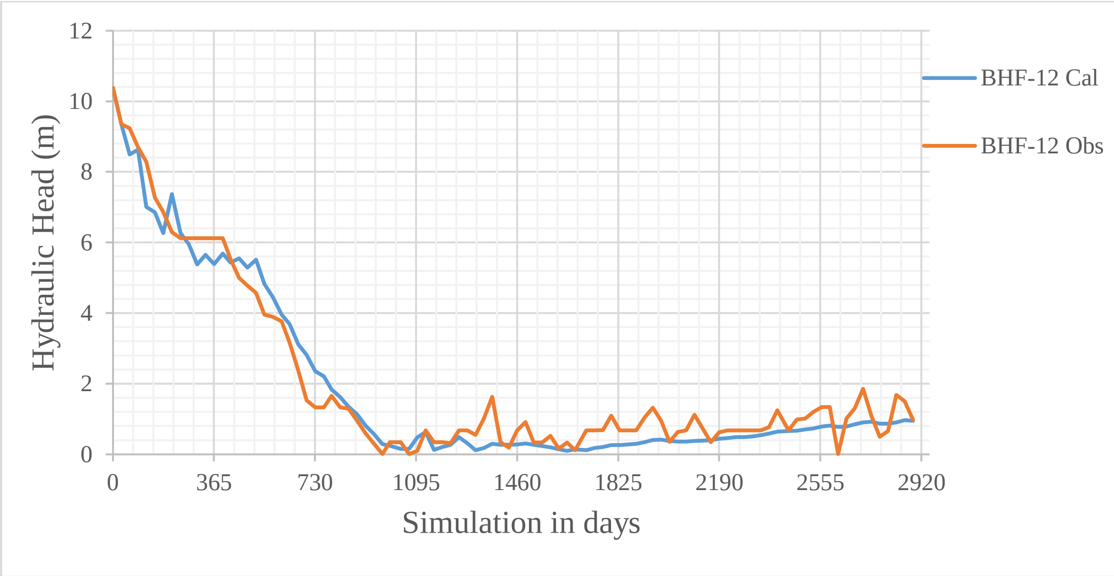


Figure 32: Flow model calibration results BHF-12

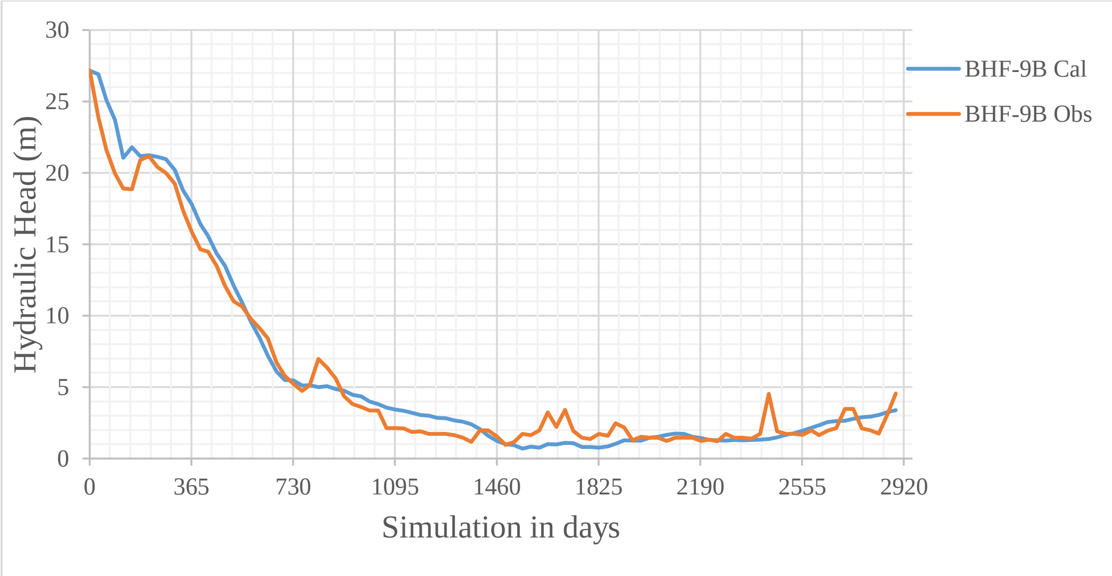


Figure 33: Flow model calibration results BHF-9B

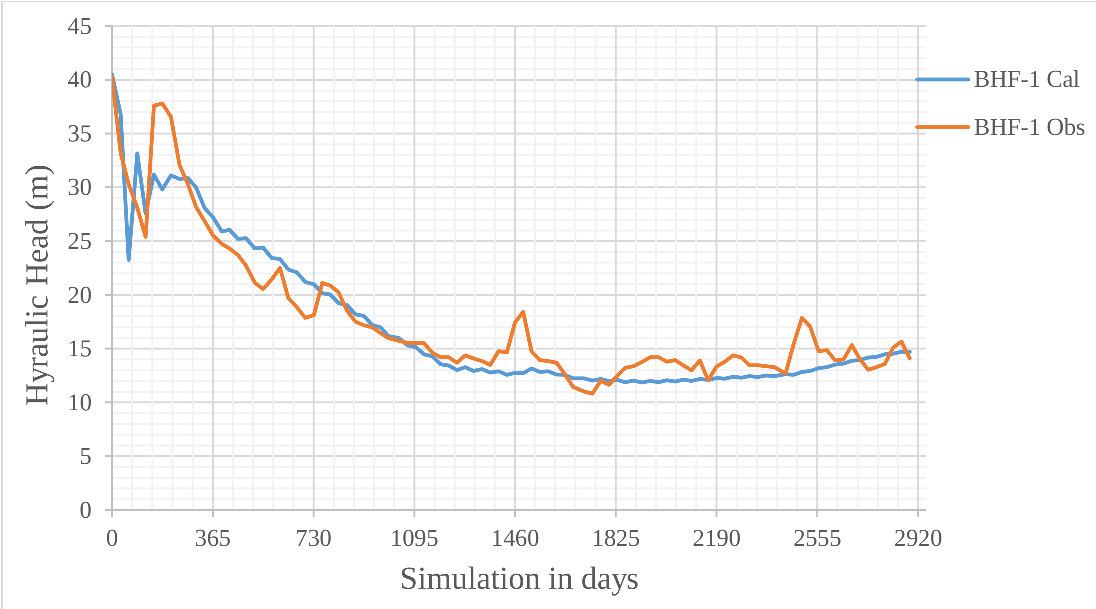


Figure 34: Flow model calibration results BHF-1

5.5.1 Flow Model Simulation to 2030 Results

Three simulation scenarios were applied on the flow model to evaluate the vulnerability of the groundwater levels to the year 2030. In the first scenario; the present rate of pumping based on the average calibrated results was simulated. In second and third scenario; the flow model was subjected to a 5% decreased and 5% increase in pumping respectively. The reason for the low level of percentage alteration was to assess the level of vulnerability of groundwater with the slightest change in pumping. This 5% change in pumping was only applied to the respective well locations and not in the whole or entire aquifer. These wells locations are however distributed across the study area and could be used as a yardstick to evaluate the groundwater levels in the study area. In other to account for the present pumping rate, we used the average calibrated results of the last five years of pumping. An average of the last 5 years' climate data was considered during the simulation. The x-axis in the graph represents number of days from May 1996 as the initial hydraulic head while the y-axis represents groundwater levels in meters.

5.5.2 Scenario 1 Present Pumping Rate

The results of the first scenario presented in Figure 35 (a) (b) and (c), clearly indicates a little or no increase in the groundwater level hence present pumping rates are not sustainable and can lead to the depletion of the groundwater if the trend continues. Groundwater level in well number BHF-1 is just above 15 m for the entire simulated period. It is important to note that this well BHF-1 is found in the western part of the aquifer which is the area with higher observed groundwater level in the aquifer. The groundwater level in both well number BHF-9B and BHF-12 is just within below 3 m and 2 m respectively. Well number BHF-12 and BHF-9B are found in the central part and northern part of the aquifer respectively. Their locations have been shown to be vulnerable to seawater intrusion and decline in observed groundwater levels. Figure 36 represents a chart of the simulated results in the FEFLOW model whose values were saved as POW files and opened in excel for comparison with observed data.

Sc. 1

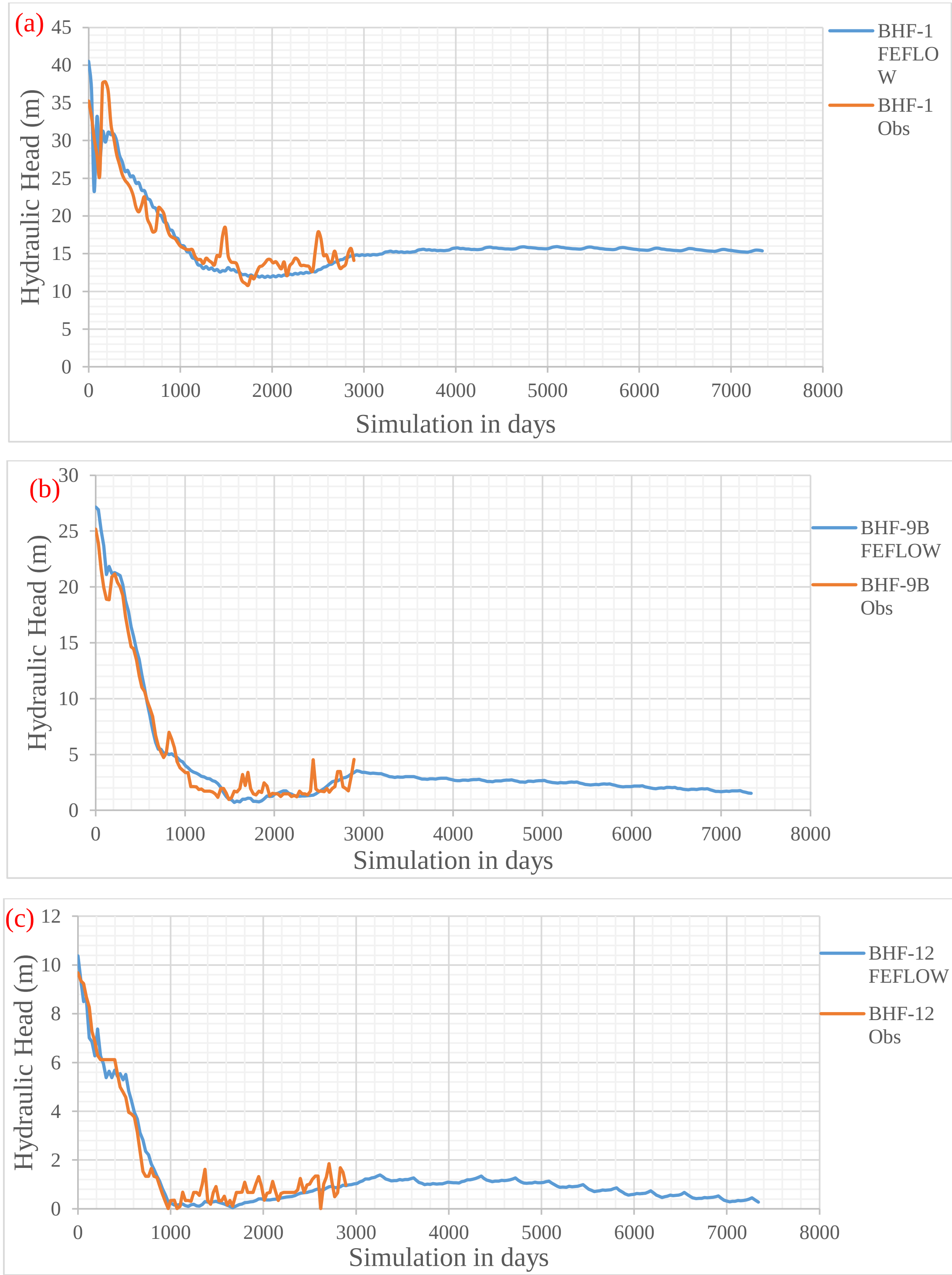


Figure 35: Prediction of groundwater level to 2030 for present pumping rate a) BHF-1, b) BHF-9B, c) BHF-12

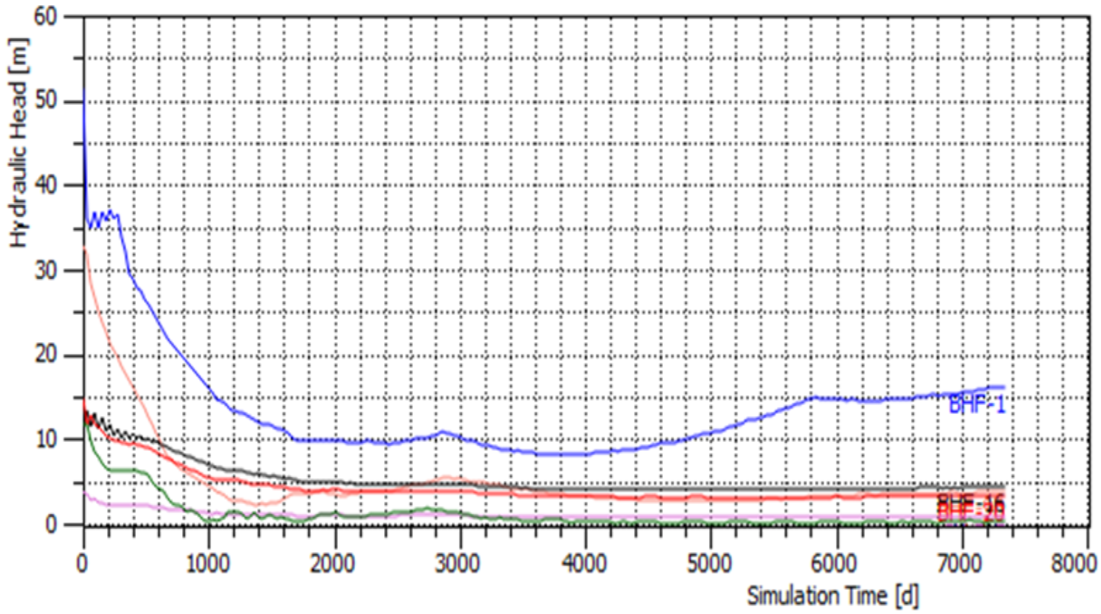


Figure 36: Flow Model Simulations Results

5.5.3 Scenario 2 5% Reduced Pumping

In the second scenario of 5% reduced pumping presented in Figure 37 (a) (b) and (c) showed a minor increase in the groundwater level. The close inspection of the figures showed a little increased in the groundwater level. This is more visible in well number BHF-12 towards the end of the simulated period in the second scenario compared with the first scenario of the same well. As shown in the calibrated Figure 32; the groundwater level for BHF-12 range from about 10 m to just above 0.1 m of freshwater. In the first scenario, the groundwater level was heading to zero as pumping was continuously applied while in the second scenario groundwater levels was increasing above 0.1. The figure clearly indicates the level of serious in the decline of the groundwater level.

Sc. 2

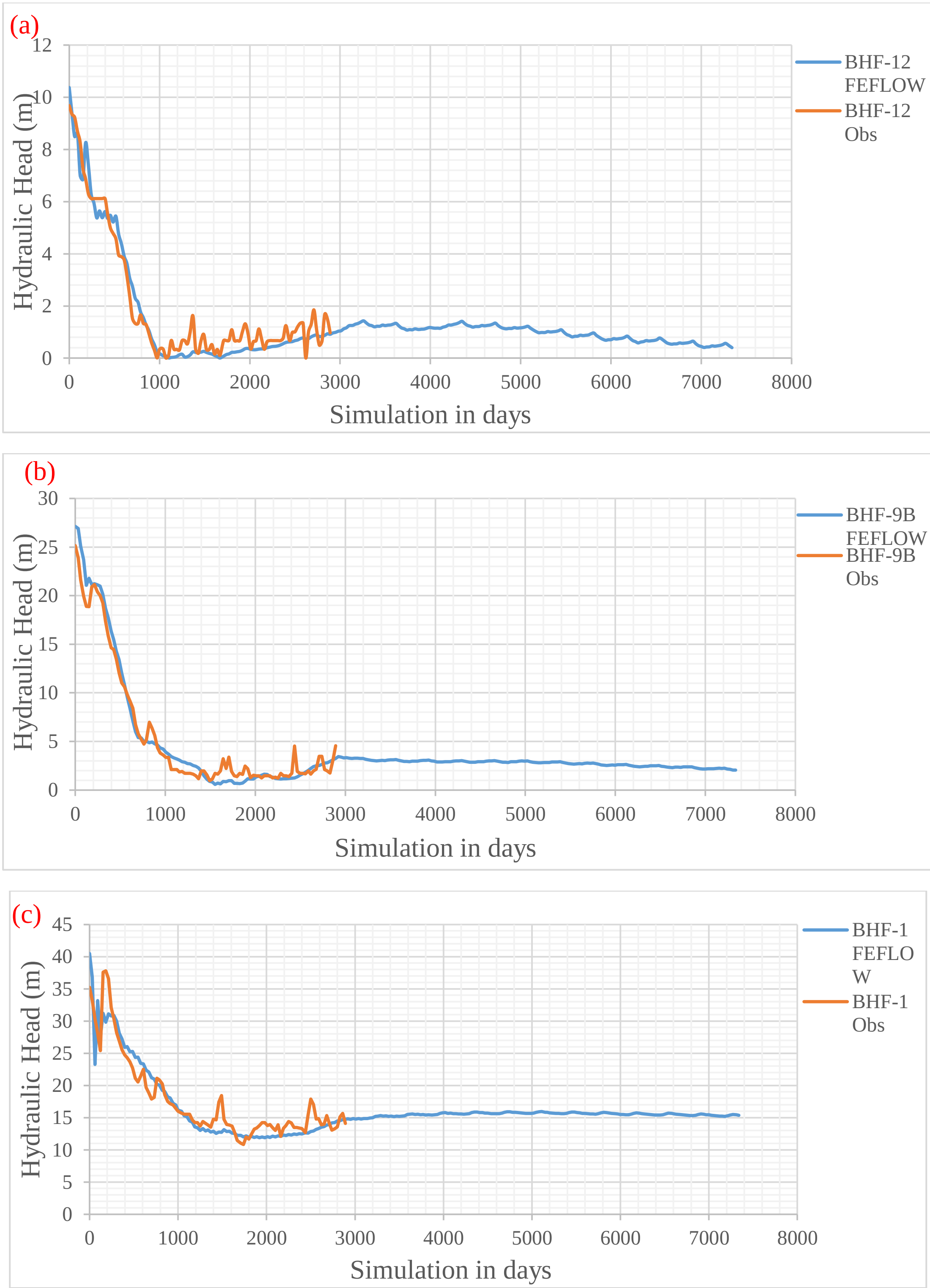


Figure 37: Prediction of groundwater level to 2030 at 5% reduce pumping a) BHF-1, b) BHF-9B, c) BHF-12

5.5.4 Scenario 3 5% Increased Pumping

In the third scenario of 5% increase in pumping presented in Figure 38 (a) (b) and (c) showed a decline in the groundwater level. For example, in well number BHF-12 for scenario 3 showed the groundwater level getting close to or almost at zero towards the end of the time step series. As shown in the calibrated Figure 34; the observed groundwater level of BHF-1 range from about 35 m to just above 10 m of freshwater. Groundwater level in well number BHF-1 decreased from above 15 m in the first scenario to below 15 m as can be observed; a steady decline in groundwater level occurred in well number BHF-1 as pumping continued. The same trend can be observed in well number BHF-9B from a groundwater level of about 2 m in the first scenario to a decline of about below 1 m in the third scenario.

Simulations results clearly indicate a severe decline of groundwater level even with a minor increase of 5% in pumping as well as little impact with 5% reduction in pumping. In a nutshell, the groundwater level in the study area is in at its lowest level and any further exploitation would only exacerbate the problem. Therefore, the only prudent act at this stage is to find corrective measures to not only increase the groundwater level or quantity but also improve its quality for future and sustainable use.

Sc. 3

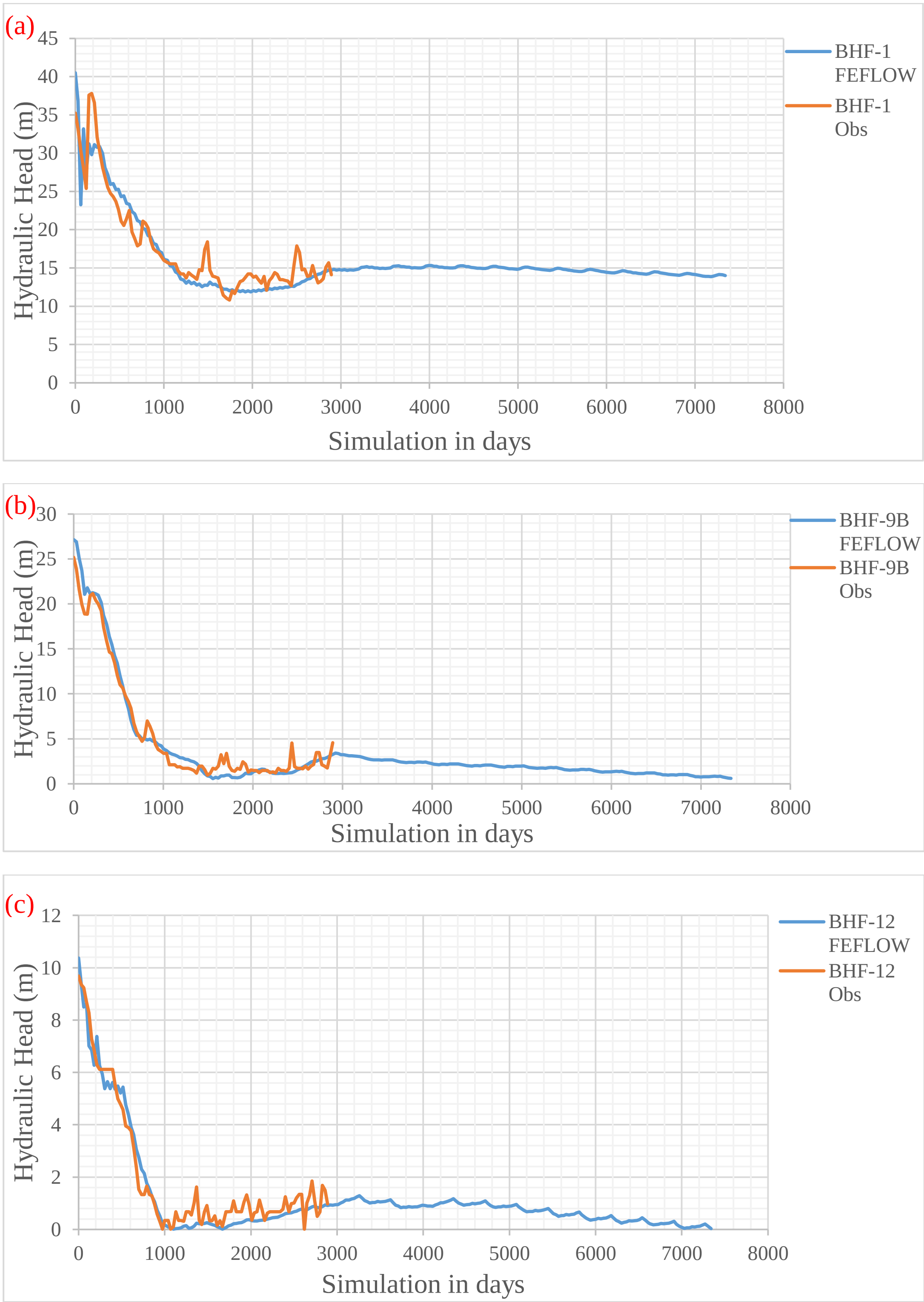


Figure 38: Prediction of groundwater level to 2030 at 5% increase pumping a) BHF-1, b) BHF-9B, c) BHF-12

Chapter 6: Solute Transport Model Development Calibration and Simulations

6.1 Introduction

Transport models simulate the migration and chemical alteration of contaminants as they move with groundwater through the subsurface. They can also be used to visualize where contamination is located and where it will likely flow given the unique set of geological, hydrological, biological and meteorological patterns at a site. Transport models require the development of a calibrated groundwater-flow model or, at a minimum, an accurate determination of the velocity and direction of groundwater-flow based on field data. The model works by simulating the movement of contaminants by advection and diffusion. The spread and dilution of contaminants occur by dispersion, removal, or release of contaminants by sorption, or desorption, or from subsurface sediments or rocks.

The process of calibration and verification in solute transport model is similar to groundwater-flow model. These involves the adjusting of values of the different hydrologeologic or geochemical conditions to reduce the disparity between the model simulations and field data. In case the adjustment of values of geochemical data does not result in an acceptable comparison with contaminant migration direction or rate; a re-evaluation of the model used for simulating groundwater-flow would be required. Monitoring of groundwater chemistry will be required to support predictive simulations using fate and transport models. The information gained from fate and transport studies and models is primarily used to evaluate human, ecological and environmental risks and to guide remediation decision-making.

6.2 Transport Model Development

This study developed a solute transport model to study the impacts of pumping brackish on seawater intrusion in the coastal aquifer of Wadi Ham. The FEFLOW model was used to simulate the groundwater concentration in space over the calibration and verification periods. Factors inputted in the model include the retardation factor which was taken as 1.0, it is defined as the ratio of average linear velocity of groundwater to the motion of the contaminant to deviate from groundwater motion. In simple terms, this means that the solute was considered to move with the same velocity of the groundwater. The other factor inputted was the molecular diffusion coefficient which was set to be equal to 0.1.

The longitudinal dispersivity was varied for calibration between a ranged of 10 to 80 m. A representative medium of the system was obtained with a longitudinal dispersivity of 65 m after different variations. An extinction depth of 2 m was assumed hence the evapotranspiration concentration boundary condition was not considered due to negligible evapotranspiration from the water table. Table 7 shows the used calibrated transport parameters. The problem settings in the model was change to mass transport state.

Table 7: Calibrated parameters for the transport model (Sherif, et al 2014)

Parameter	Value
Retardation factor	1.0
Longitudinal dispersivity α_L	65 m
Transverse dispersivity α_T	0.65 M
Vertical dispersivity α_V	0.065 m
Molecular diffusion coefficient	0.1

6.3 Calibration and Validation Results

The transport model required the introduction of groundwater solute concentration which was expressed in terms of total dissolved solids (TDS). Along the coastline of the Gulf of Oman; a constant head of 35000 mg/l salt concentration in groundwater was considered along that side of the boundary of the study domain. A freshwater concentration of 100 mg/l in TDS was considered where a freshwater flux is encountered through the main three Wadi flux areas. Otherwise, the concentration gradient across the boundary is set equal to zero. The initial salt concentration in groundwater distribution measured in December 1988 was used in the numerical modeling are presented in Figure 39. Longitudinal dispersivity was the main parameter varied to obtain an acceptable salinity levels compared with previous observed and simulated data. As shown in Figure 39 initial salt concentration in groundwater clearly showed that from 5001 mg/l to 35, 000 mg/l extends 3.4 km inland while the rest of the western part of the aquifer falls below the 5001 mg/l concentration levels. The zone that falls below 5001 mg/l concentration can be freshwater zones according to the standardized water salinity Table 2.

Simulation results from the initial salt concentration in groundwater distribution at the end of verification period is presented in Figure 40. These results were compared with concentration distribution in the study area at the end of their verification period (Sherif, et al 2012) in Figure 41. Despite the limited available data of salt concentration in groundwater distribution, the simulation result is consistent with (Sherif et al. 2012) findings with regards to the salinity distribution. Salt concentration in groundwater increases from the southern eastern part of the aquifer towards inland; a result consisted with previous studies done in the same area. The results are also consisted with the farmer's general perception that freshwater is encountered at about 5 km from the shoreline. In the eastern southern part of the aquifer seawater intrusion is shown to move towards inland within the aquifer during stress period 36 of 1096 days.

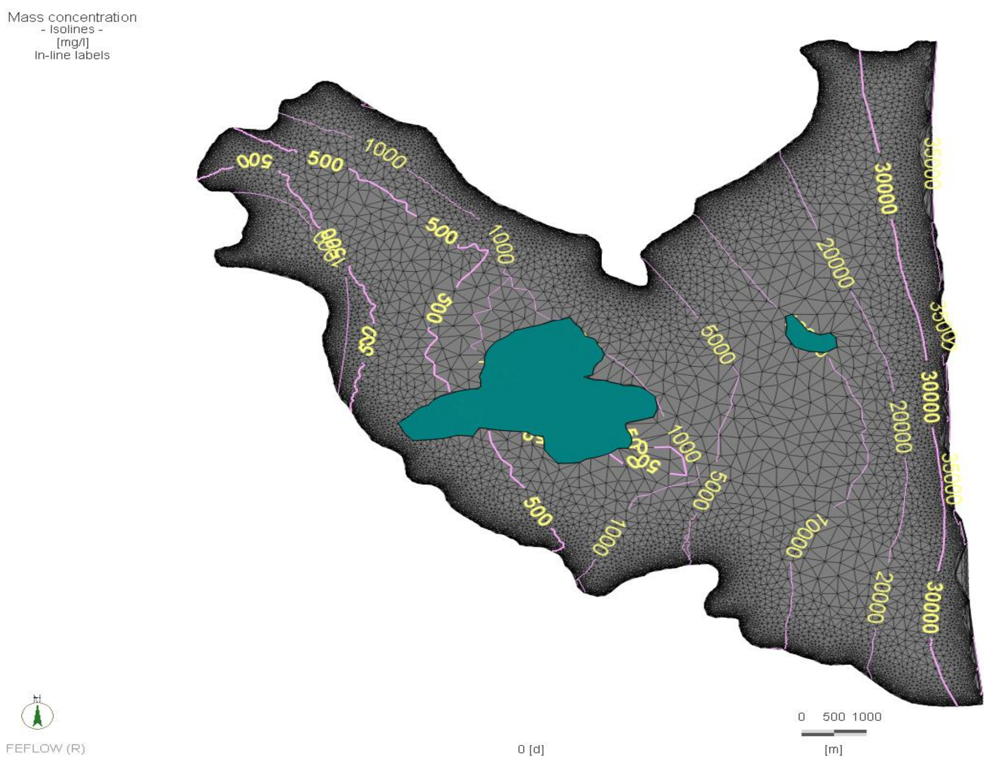


Figure 39: Initial groundwater concentration (mg/l) December 1988 (Sherif, et al 2012)

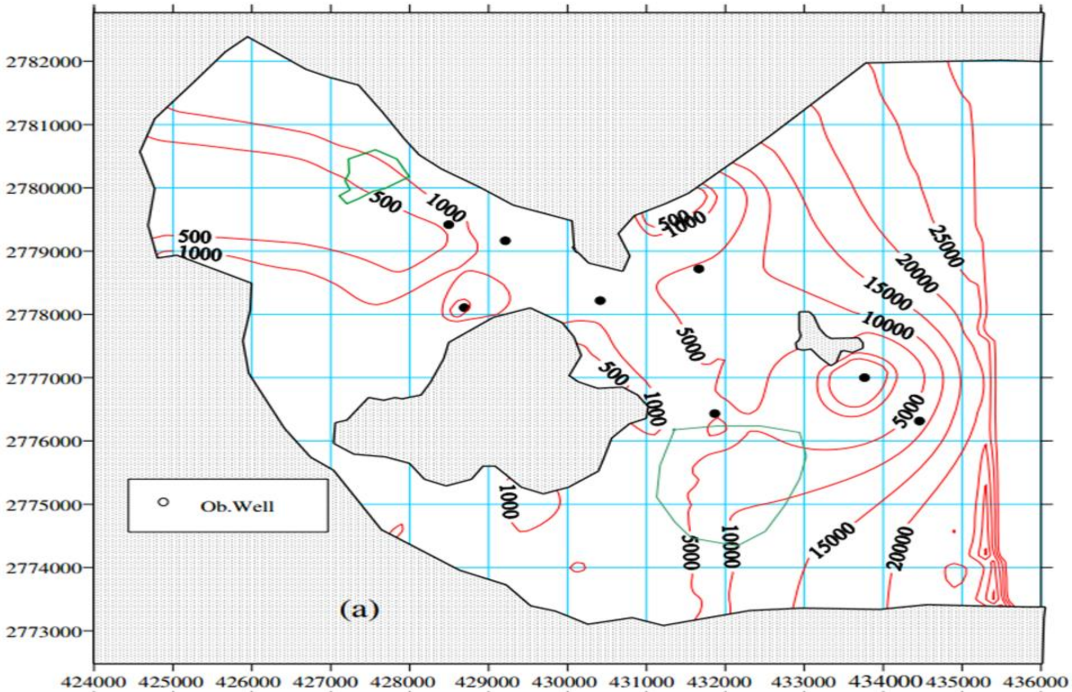


Figure 40: Salt concentration in groundwater distribution in the study area at the end of verification period (Sherif, et al 2012)

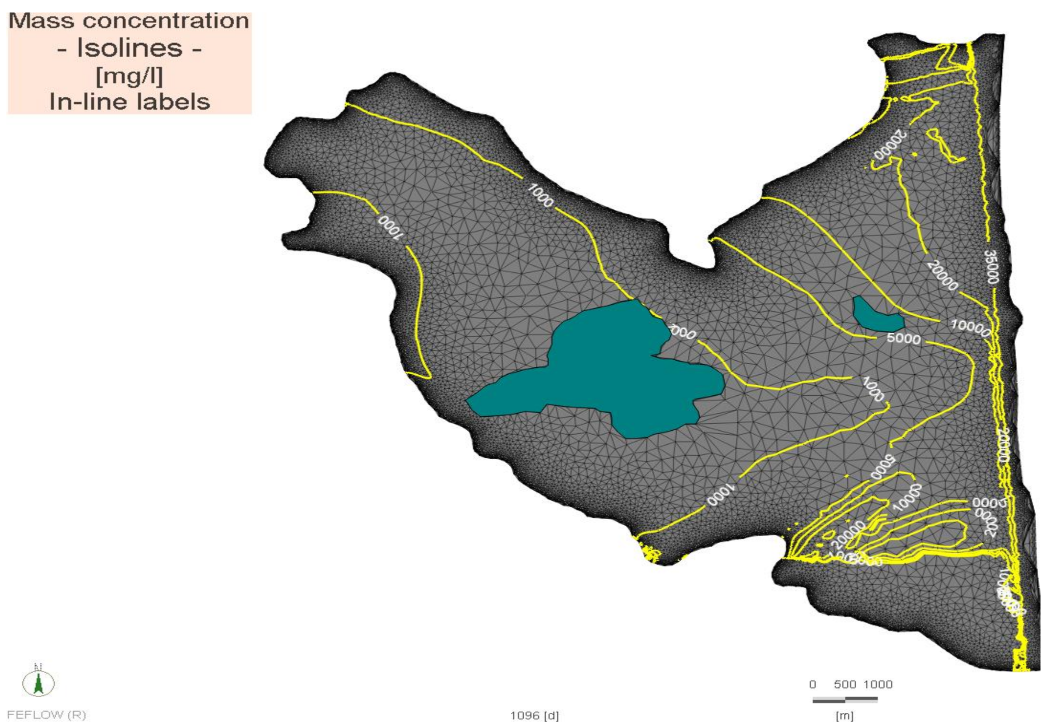


Figure 41: Salt concentration in groundwater distribution in the study area at the end of verification period FEFLOW

6.4 Simulation of Pumping Brackish Water

The calibrated transport model provided an insightful information as to the main locations of brackish water within the aquifer. This information was used in the application of simulation scenarios of pumping brackish water from the coastal aquifer to assess its impacts on the control of seawater intrusion. Groundwater is pumped from the sand and gravel aquifer for irrigation purposes in the coastal aquifer of Wadi Ham. Three well fields are in operation for the domestic water supply by the Federal Electricity and Water Authority. The range of pumping from these fields is presented in table 8 (Sherif, et al 2014). As shown in Table 8**,** the average total pumping in the study area is 18325 m^3/day or 6.6887 MCM/year. There are currently 11 active wells in the study area as per Table 6 (Sherif, et al 2006), this gives an estimated average pumping rate of 1030 m^3/day per well.

In this study, several pumping wells were installed known as multilayer wells in the model. The zone of freshwater thickness in Wadi Ham aquifer is varying from less than 1 m near the shoreline to about 20 m at a distance of 3 km from the shoreline (Sherif et al 2012). Figure 42 and Figure 43 shows the installed pumping wells location, and their features and characteristics in the multilayer well editor respectively.

Table 8: Range of groundwater pumping from different fields (Sherif, et al 2014)

Well field	Pumping rate (m^3/day)		Average (m^3 /day)	Volume/year (MCM)
	max	min		
Shaarah	5500	1200	1.1772	1.1772
Fujairah	1800	1200	1500	0.5475
Kalbha	16500	5500	13600	4.96
Total			18325	6.6887

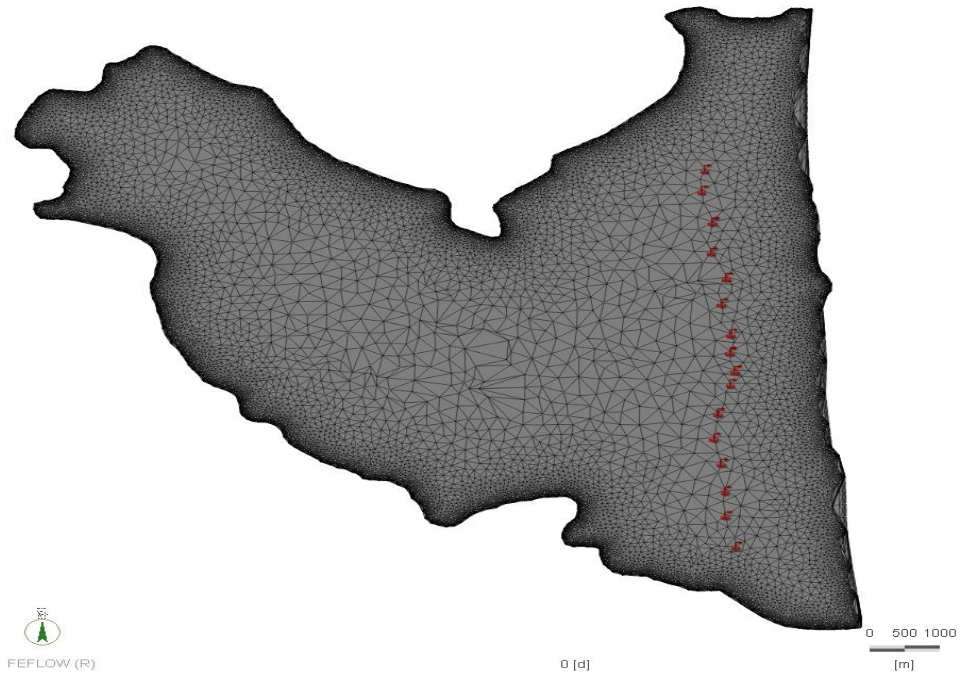


Figure 42: Installed multilayer pumping wells

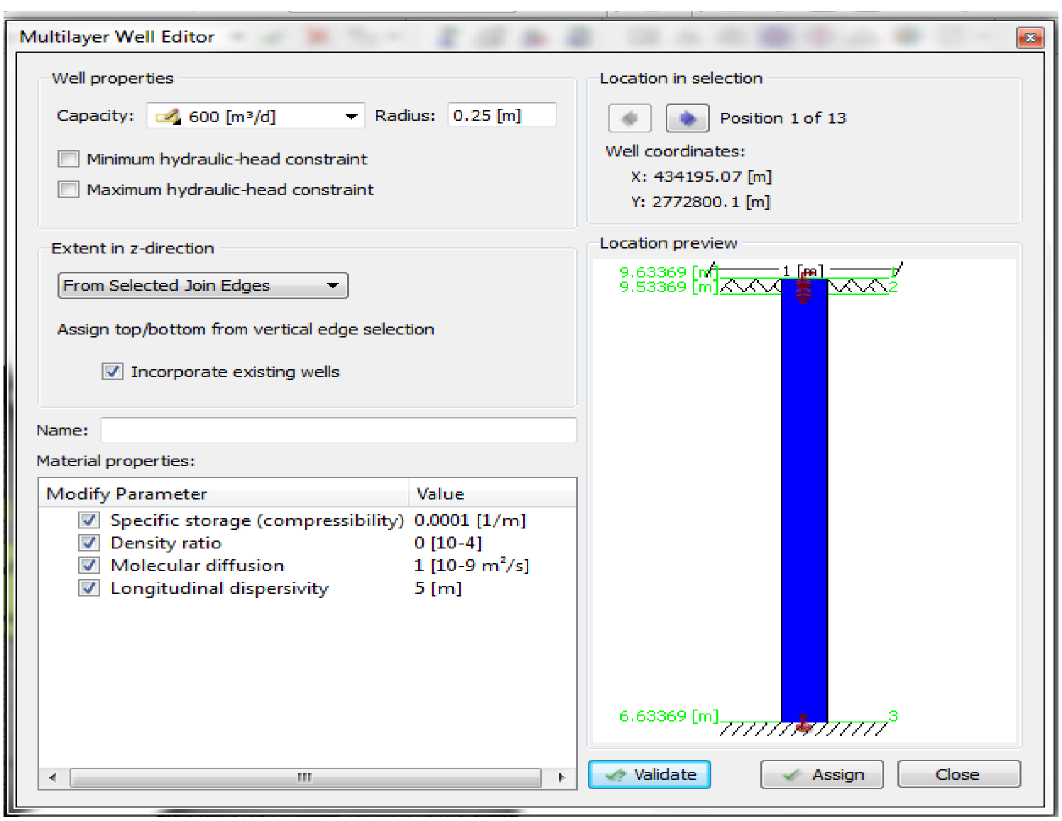


Figure 43: Multilayer Well Editor

Pumping of brackish water in coastal aquifers requires appropriate understanding and determination of pumping rates, wells location and number of wells. Three simulation scenarios are presented to assess the most appropriate pumping rates, number of wells and optimum wells location from the shoreline.

In this section, we assess these three parameters and checked which of them has the most impact in terms improvement in salt concentration in groundwater using the isoline 15000 mg/l at 4018 days of simulation. Isoline 15000 mg/l is within the range of very saline water and it was used as a yardstick to assess the progression of seawater intrusion in the aquifer. The movement of this isoline 15000 mg/l was measured at the three major locations of A, B, and C marked on the Figure 44**.** Location A is the area with the lowest hydraulic conductivity in the aquifer while location B is in the area with highest hydraulic conductivity. Location C is also within the area with the highest hydraulic conductivity and it is the area with highest know seawater intrusion level. The y-axis in the plotted figures represents the movement of isoline 15000 mg/l in meters from the shoreline with respective simulated scenarios.

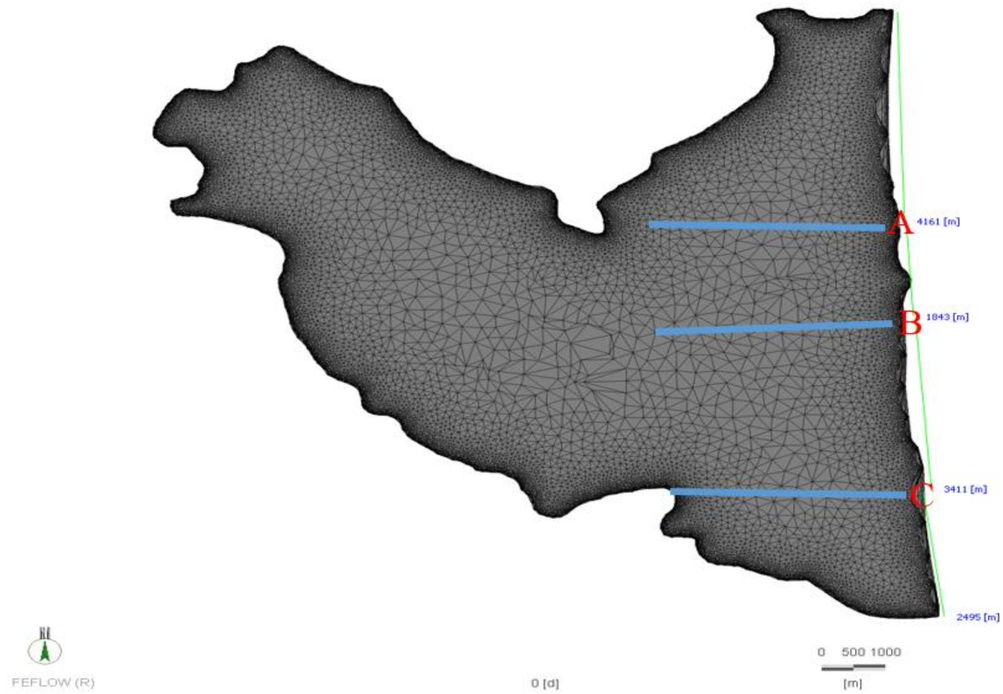


Figure 44: Location of isoline 15 000 mg/l measurement from the shoreline

In Scenario-1, there were 14 wells installed with a pumping rate of 600 m^3/day per well which is a total of 8400 m^3/day in the whole aquifer. The number of wells and pumping rates per well were kept constant throughout the simulation. Pumping wells location from the shoreline distances were varied as shown in Table 9. This was done to determine the most appropriate distance where wells should be installed from the shoreline. Distance change in isoline 15000 mg/l from the shoreline was recorded for each simulated scenario location A, B and C respectively. The initial location of 15000 mg/l at A, B and C before simulation are shown as 2066, 1210, 1833 respectively for all the simulated scenarios.

Variation of isoline 15000 mg/l at variable locations of pumping wells starting from the initial point was plotted against the respective distance change in the three identified locations of A, B and C in as shown in Figure 45. The figure shows that at location (A) initial distance was steadily reduced as distance of pumping location was increased, meaning the isoline 15000 mg/l moved towards the shoreline. This is consisted with previously transport model calibration results Figure 40 where it is shown that isolines at location A moved towards the coast. At location B, the distance was steadily decreased as pumping locations were place further inland and had minor variable changes due to the high level of interaction in the area. Isoline 15000 mg/l moved further inland for location C as pumping location was change which is the normal trend for this area as it has been shown to be affected with seawater intrusion. This trend was reversed after well locations were place at 1100 m from the shoreline and this was consolidated at 1500 m. The highest decline in distance of the isoline 15000 mg/l was at wells locations of 1500 m from the shoreline. This suggest that pumping of brackish water could be most effective at wells location of 1500 m from the shoreline. Figure 46 shows the location of isoline 15000 mg/l at 4018 days for 1800 m wells location.

Table 9: Pumping wells varied distances with respective simulated distance results

S1	**N (wells)**	**Q m^3/day**	**Dis (m)**	**A (m)**	**B (m)**	**C (m)**
Initial	0	0	0	2066	1210	1833
1	14	8400	500	1315	308	1993
2	14	8400	800	1275	202	2443
3	14	8400	1100	1209	299	1535
4	14	8400	1500	1264	291	525
5	14	8400	1800	1334	276	355

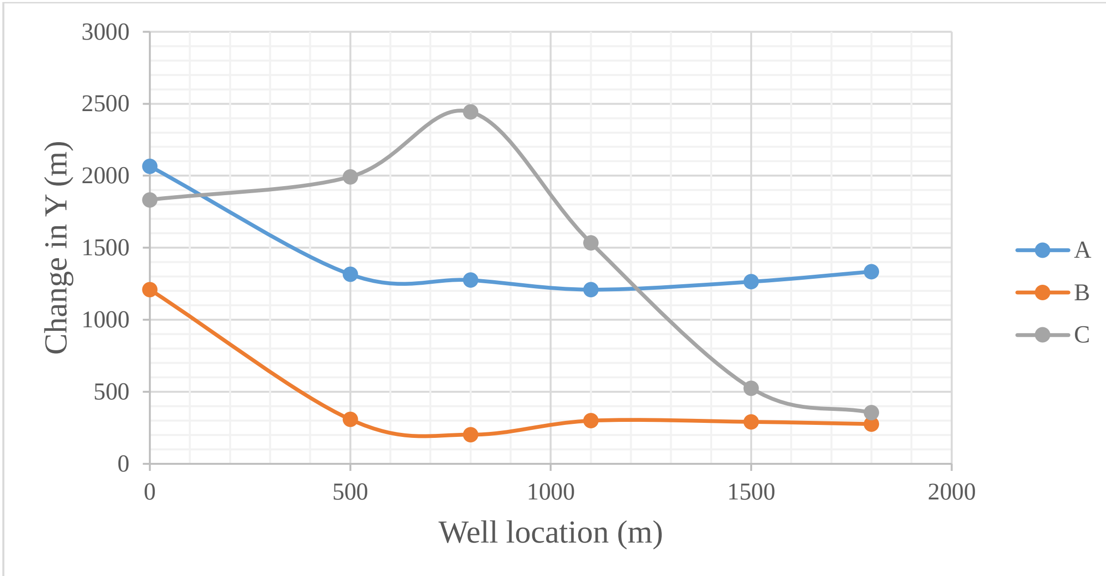


Figure 45: Variation of isoline 15000 mg/l at 4018 days at variable well distances

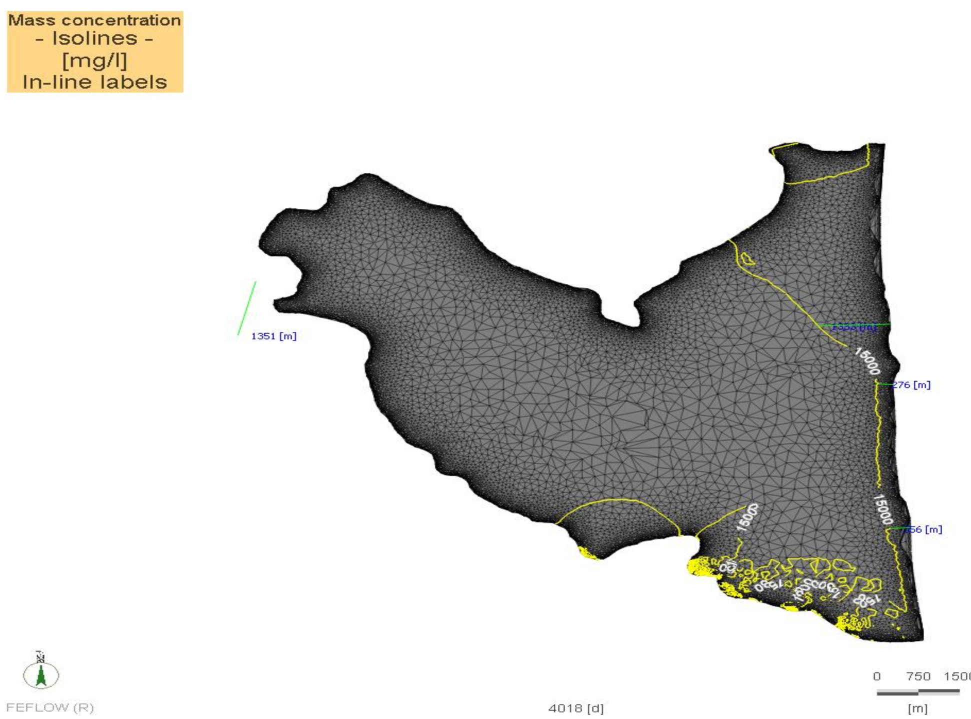


Figure 46: Location of isoline 15000 mg/l at 4018 days for 1800 m wells location

In Scenario-2, there were different number of wells installed with a pumping rate of 500 m^3/day per well. The number of pumping wells were varied as shown in Table 10, with constant pumping rate per well and constant distance. This was done to determine the number of wells most suitable for pumping brackish water in the study area.

In the first run, there were 8 wells installed and result showed isoline 15000 mg/l moved towards the coast at location A, and B, while it moved further inland at location C. This is the normal trend for these respective areas as per calibrations and field situation. This trend was however reversed as the number of wells were increased to 16 as it can be noticed on the Figure 47 at location C, and for A, and B, its change towards the coast was consolidated. This simulation showed that at 16 number of pumping wells at a total rate of 8000 m^3/day as the highest level of improvement in the movement of isoline 15000 mg/l towards the coast. Figure 48 shows the location of isoline 15000 mg/l at 4018 days for 16 pumping wells.

Table 10: Number of installed pumping wells with respective simulated distance results

S2	**n (wells)**	**Q m^3/day**	**A (m)**	**B (m)**	**C (m)**
Initial	0	0	2066	1210	1833
1	8	4000	1229	300	2321
2	10	5000	1230	290	2513
3	12	6000	1278	297	2310
4	14	7000	1260	276	2201
5	16	8000	1248	296	1142

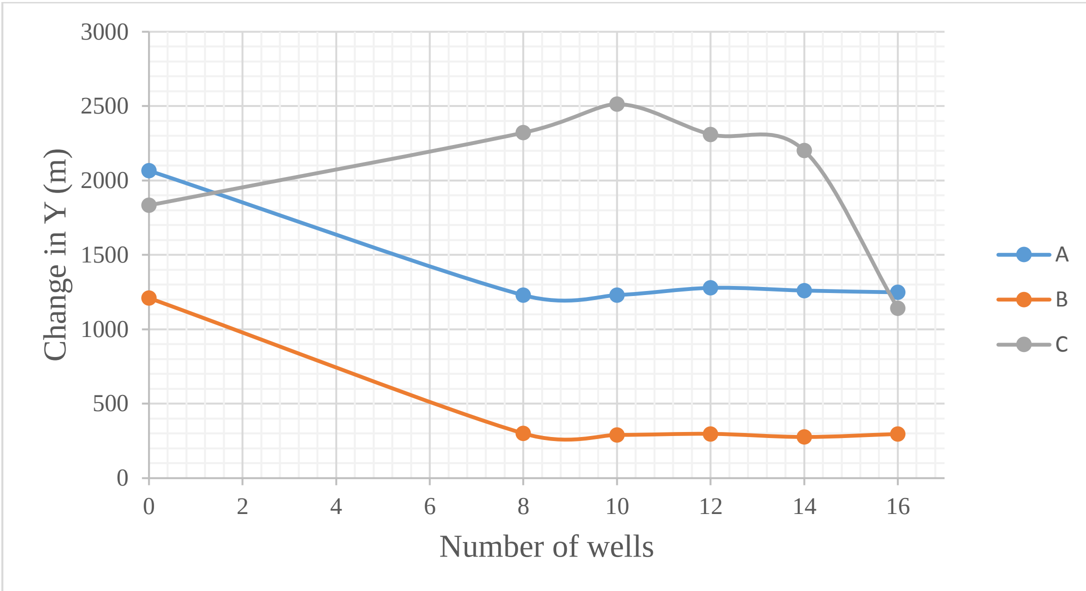


Figure 47: Variation of isoline 15000 mg/l at 4018 days of variable number of well

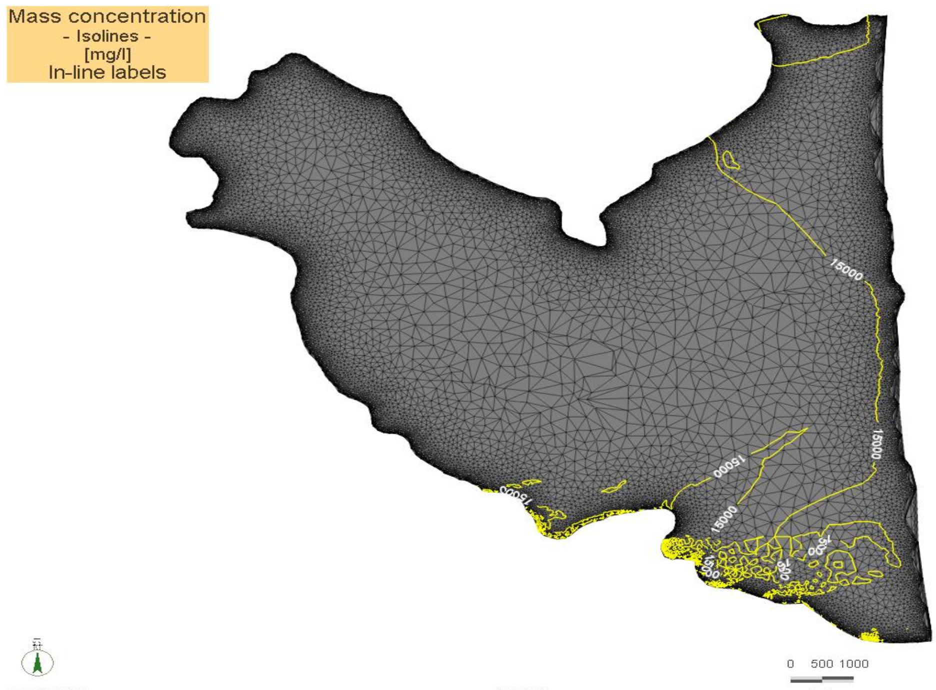


Figure 48: Location of isoline 15000 mg/l at 4018 days for 16 pumping wells

In Scenario-3, there were constant number of wells installed at a constant location while the rate of pumping per well was varied in Table 11**.** There were 10 wells installed at about 1500 m from the shoreline and different rates of pumping were assigned during each run. This was done to determine the rate of pumping per well most suitable for pumping brackish water in the study area.

In the first run, a pumping rate of 600^3/day was applied for the 10 installed wells and result showed isoline 15000 mg/l moved towards the coast at location A, and B, while it moved further inland at location C. This trend shown in Figure 49 is however reversed as pumping rate was increased to 800 m^3/day per well which is 8000 m^3/day of total pumping, the same as previously obtained value of 8000 m^3/day total pumping for 16 wells at 500 m^3/day. Location C is the area of focus due to the fact it is the area where seawater intrusion is mainly occurring and its reversal suggest an improvement in its control. Figure 50 shows the location of isoline 15000 mg/l at 4018 days for 900 pumping rate per well.

Table 11:Pumping rates variation per well with respective simulated distance results

S3	**n (wells)**	**Q m^3/day**	**A (m)**	**B (m)**	**C (m)**
Initial	0	0	2066	1210	1833
1	10	6000	1430	293	2500
2	10	7000	1365	288	2625
3	10	8000	1315	299	1244
4	10	9000	1297	300	1554
5	10	10000	1219	300	2093

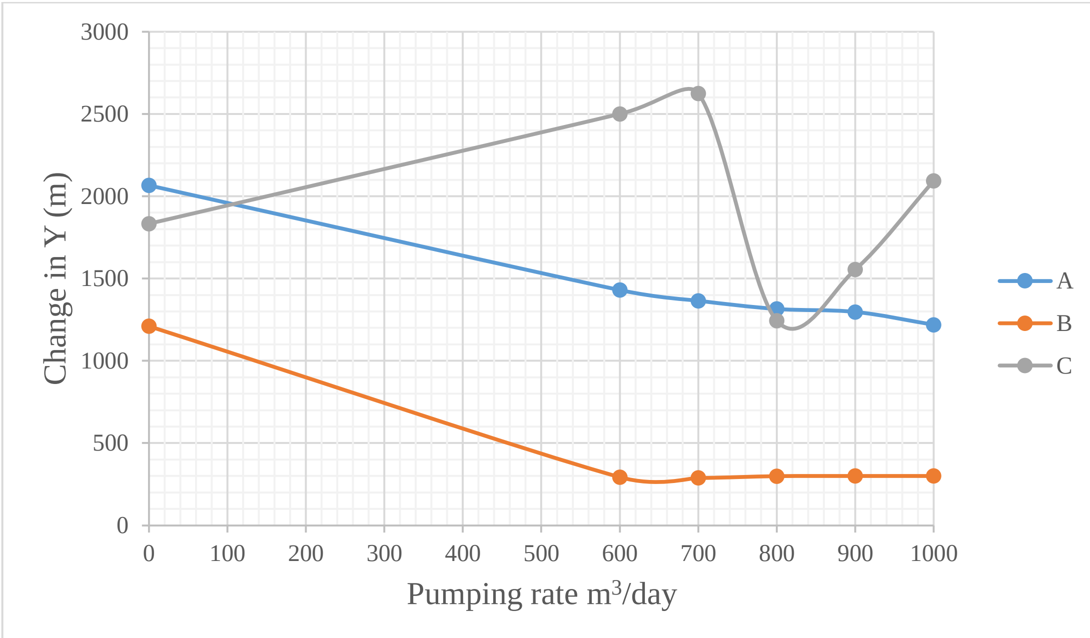


Figure 49: Variation of isoline 15000 mg/l at 4018 days of variable pumping rates

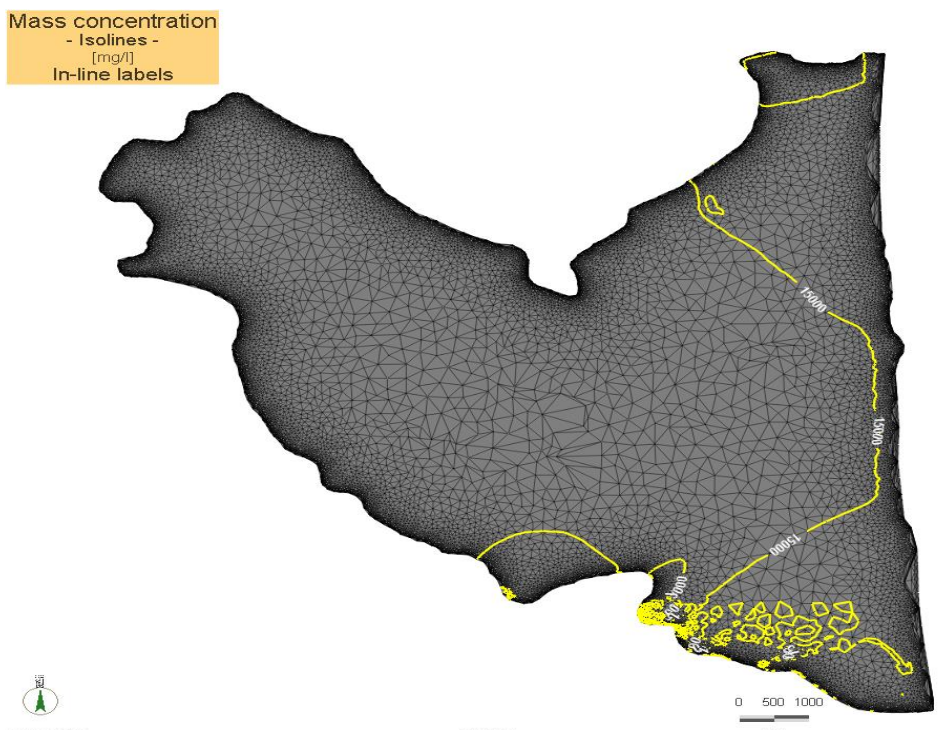


Figure 50: Location of isoline 15000 mg/l at 4018 days for 900 pumping rate per well

6.5 Impacts of Pumping Brackish Water on Seawater Intrusion

As discussed in the previous section, scenario 1 showed that installing wells at a location of 1500 m from the shoreline was the ultimate wells location. Scenario 2 showed 16 pumping wells at a total rate of 8000 m^3/day as the rate with the most improvement in the movement of isoline 15000 mg/l towards the coast. Finally, scenario 3 showed at a total pumping of 8000 m^3/day for 10 installed wells had the most improvement. It is important to note that the wells spacing was different for the different simulated scenarios and as such minor variations in the isoline change.

In this final scenario of pumping brackish compared with non-pimping, we choose the wells location as 1500 m from the shoreline, total pumping rate of 8000 m^3/day for 16 installed wells at an average spacing of 500 m between wells. This was used to simulate the impacts of pumping brackish water on seawater intrusion in the aquifer. These locations were selected based on the above estimated locations of pumping wells as well as pumping rates per well. Total pumping per day from the 16 installed wells was 8000 m^3/day which equals 2.920 MCM/year and represents 44% of total pumping in the aquifer as calculated below. The application of 500 m^3/day pumping per well is below the average total pumping per well of 1030 m^3/day discussed section 6.4 in the study area. This amount is feasible since it represents 44% of total pumping in the study area as previously shown in Table 8.

Percentage of applied pumping in the aquifer calculation:

$$P = \frac{AP}{TP} * 100\%$$

Where,

P = Percentage of pumping,

AP = Applied pumping (MCM/year)

TP = Total pumping (MCM/year)

For 500 m^3/day pumping per well for 16 wells

TP = 6.6887 MCM/year

AP = 500m^3/day *16 wells = 8000 m^3/day *365 days = 2.920 MCM/year

Therefore, $P = \frac{2.920}{6.6887} * 100\%$

P = 44%

6.5.1 Simulation Results Discussion

The results of the calibrated model without pumping are compared with those of pumping scenario applied in the model. Each stress period was compared with its same stress period under the two compared conditions of pumping and non-pumping. An increase in groundwater salinity distribution from the eastern southern part of the aquifer was observed after 1461 days of simulation in the year 2020. Salinity distribution increase further inland in the eastern southern part intruding into the well number BHF-5 under the scenario of non-pumping. Simulated results of applied pumping showed a reduction in groundwater concentration in the eastern southern part of the aquifer mostly affected with the seawater intrusion problem.

Simulation results are shown in the following figures which reveals a steady increase in salt concentration in groundwater distribution from the eastern southern part of the aquifer during the period of non-pumping. On the other hand, a reduction in salt concentration in groundwater distribution is observed in the period of pumping. The stress periods of non-pumping are presented in figure (a) of each respective stress period. Higher concentration of groundwater in the form of isolines can be noticed during the entire period of the non-pumping in all the stress periods. On the other hand, the figure (b) represents the stress period with pumping and as can be noticed there is a significant reduction in salt concentration in groundwater distribution. The eastern southern part of the aquifer is the major focus because literature has shown it to be the area with highest level of seawater intrusion. A closer look at the isolines reveals a much lower salt concentration in groundwater in the upper part of aquifer and it was not affected during the pumping. This is because the applied pumping in the intrusion zone is far away from that part of the aquifer. Salinity levels in the upper part of the aquifer remained in the range of 500 to 1000 mg/l under which is within the standard of freshwater fit for agricultural use and other activities.

Initial salt concentration in groundwater as can be observed in Figure 39 showed a concentration of 5000 mg/l to 500 mg/l from the middle of the study area towards the western part of the aquifer. The application of pumping showed the movement of lower isolines with concentration of 500 mg/l towards the eastern or coastal part of the aquifer as observed in the figures during different stress periods. This application greatly reduced salt concentration in groundwater in the southern eastern part of the aquifer which suggests pumping brackish would be greatly beneficial in the control of seawater intrusion.

Figure 51 (a) without pumping of brackish water showed the movement of isolines 35,000 mg/l towards inland in the eastern southern part of the aquifer. In the same stress period of 60-1827 days with pumping in Figure 51 (b) a salt concentration in groundwater reduce to a maximum level of 20,000 mg/l for the same area. Lower part of the aquifer in the southern eastern part showed a higher density of isolines concentration, this could be as a results of higher TDS values since the area has the highest level hyradulic conductivity. Dense isolines represent pockets of different salt concentration in groundwater charateristics from 1000 to 35000 mg/l.

Isoline 35000 increased further inland in Figure 53 and Figure 54 after 3653 and 4018 days of simulations respectively for the period of non-pumping while the maximan isoline observed for pumping in the same area for the same period remained 20000 mg/l. The same trend was observed in Figure 55 to Figure 57 with islone 35000 mg/l moveming towards inland in the scenario of non-pumping while it decreseaed to approximately to a level of 10000 in the pumping scenario. This trend of reduction of salt concentration in groundwater distribution from 35000 to 20000 mg/l in the southern eastern part of the aquifer was also observed in all the simulated periods.

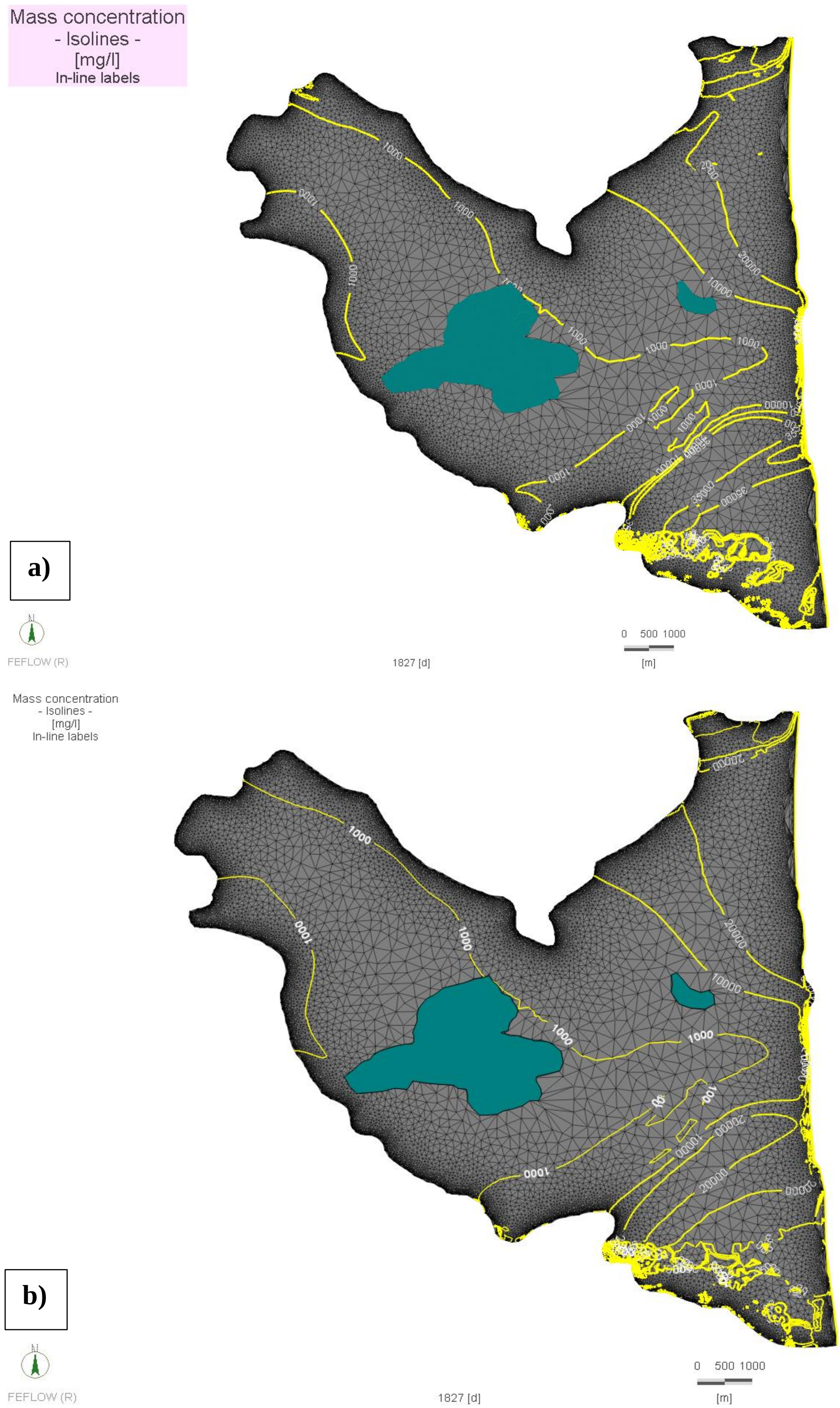


Figure 51: Stress period 60-1827 days; a) without pumping, b) with pumping

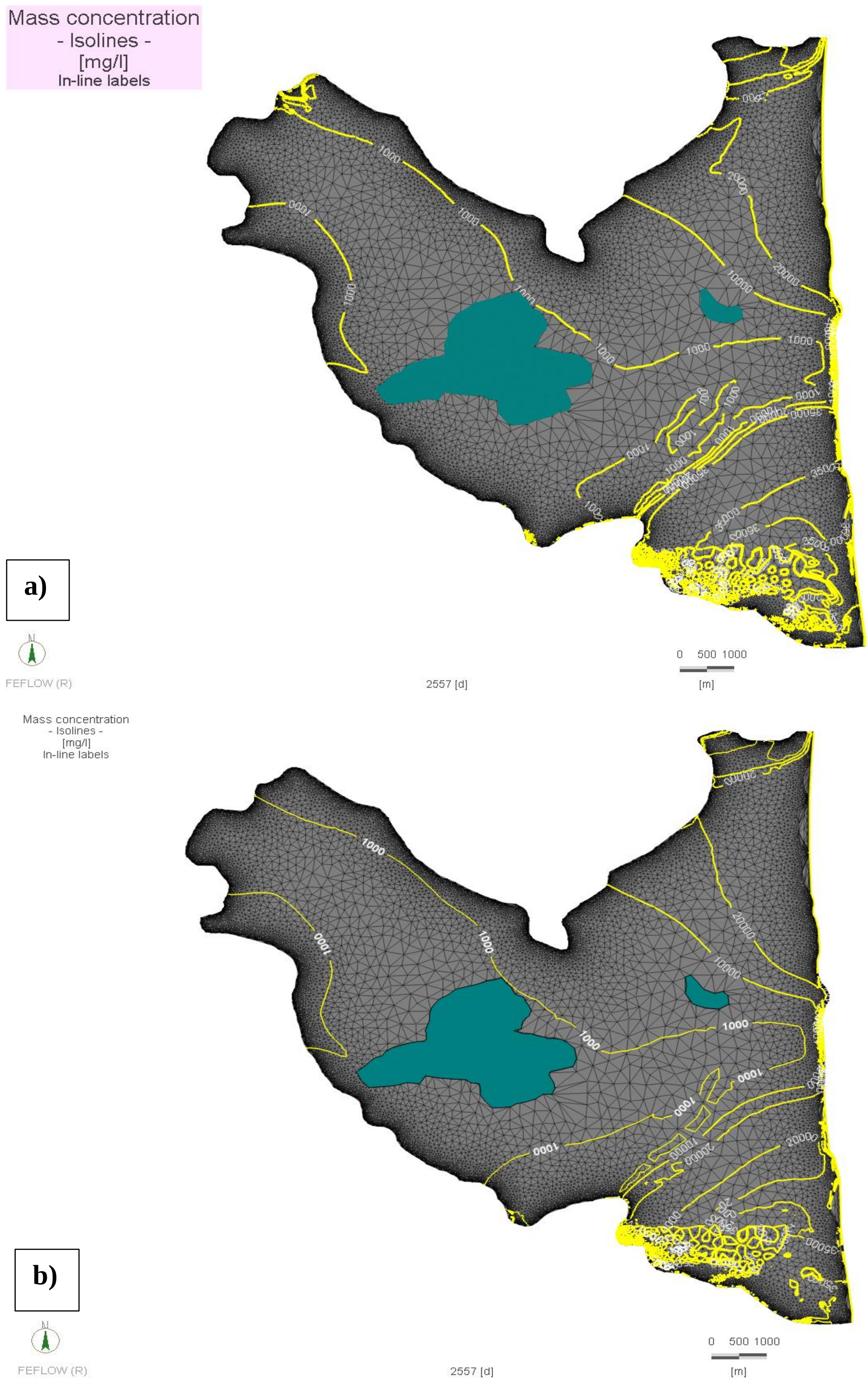
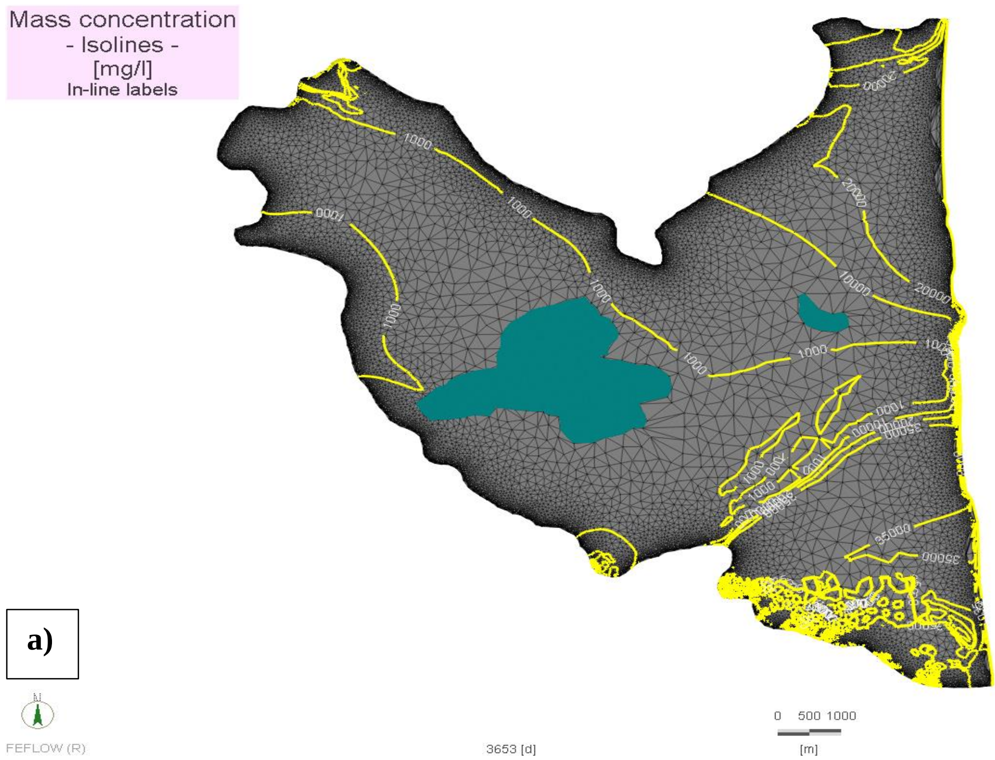


Figure 52: Stress period 84– 2557 days; a) without pumping, b) with pumping



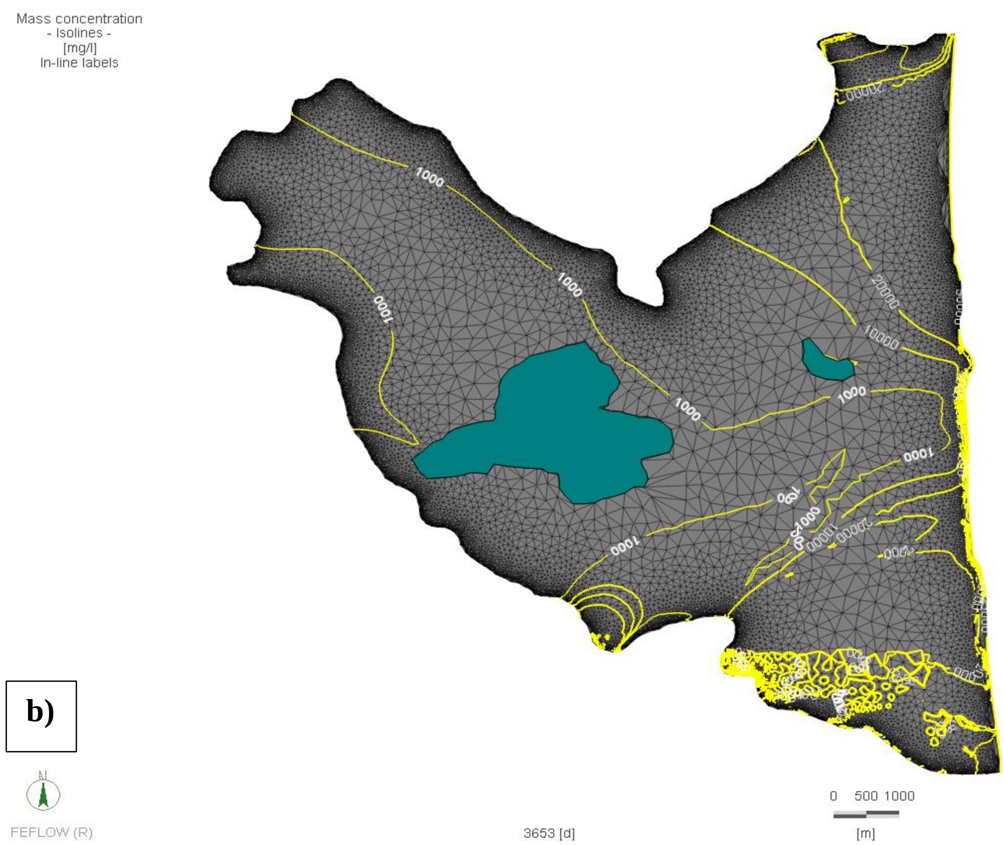


Figure 53: Stress period 120-3653 days; a) without pumping, b) with pumping

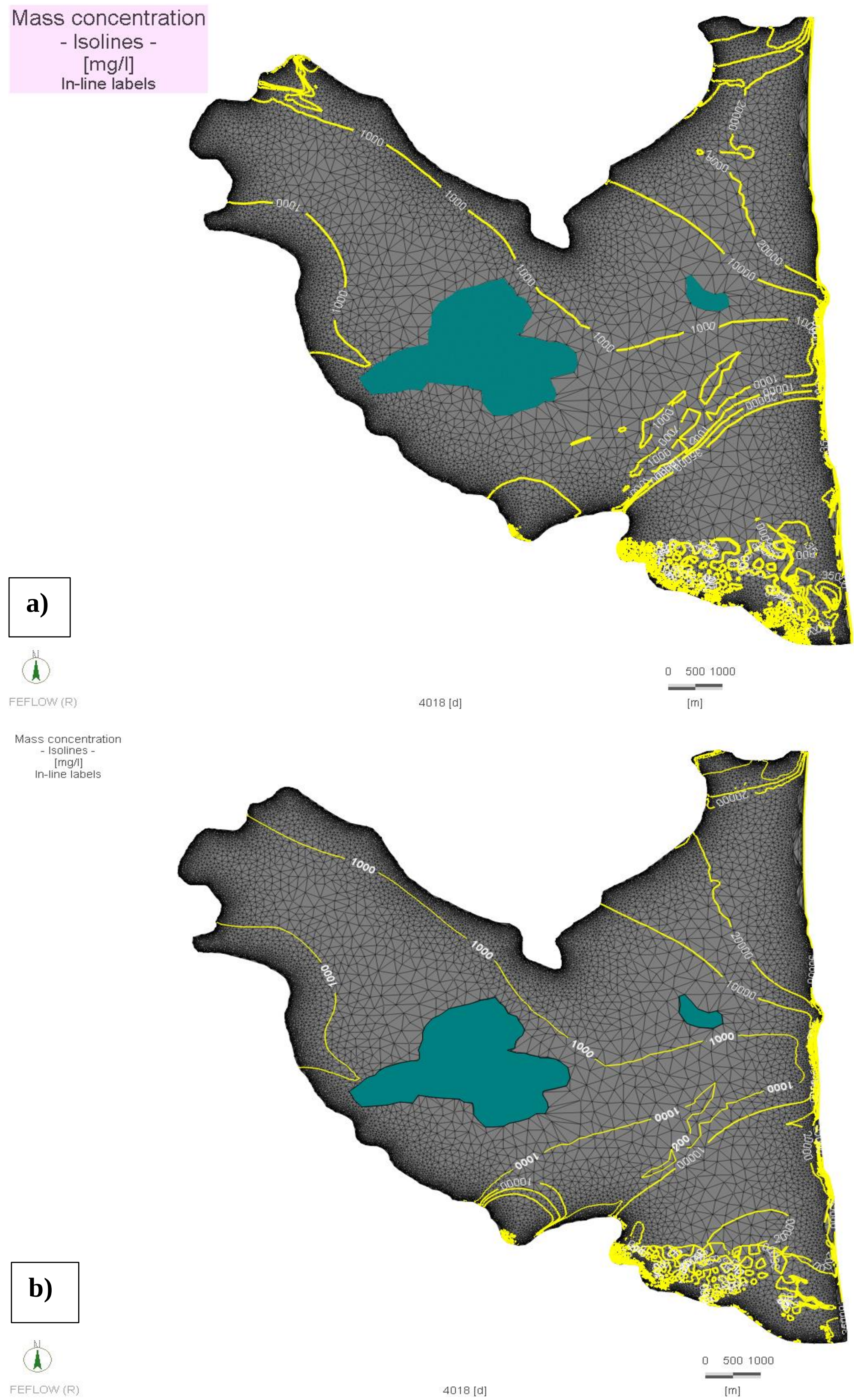
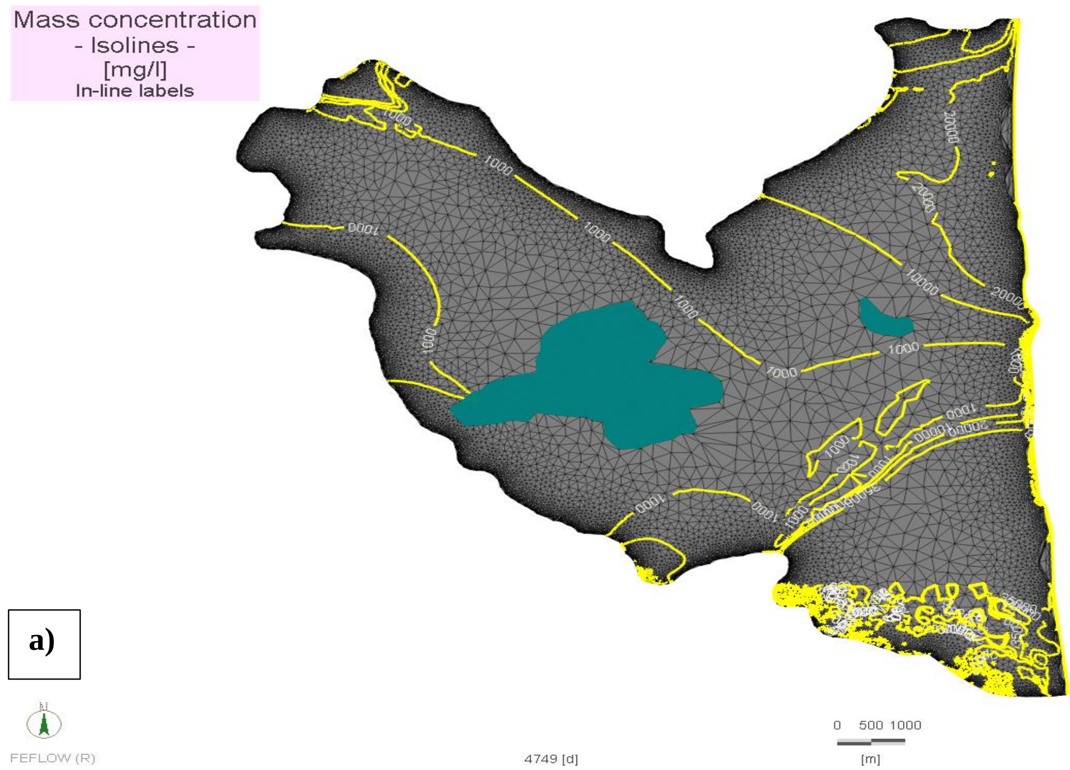


Figure 54: Stress period 132-4018 days; a) without pumping, b) with pumping

Figure 55: Stress period 144– 4383 days; a) without pumping, b) with pumping



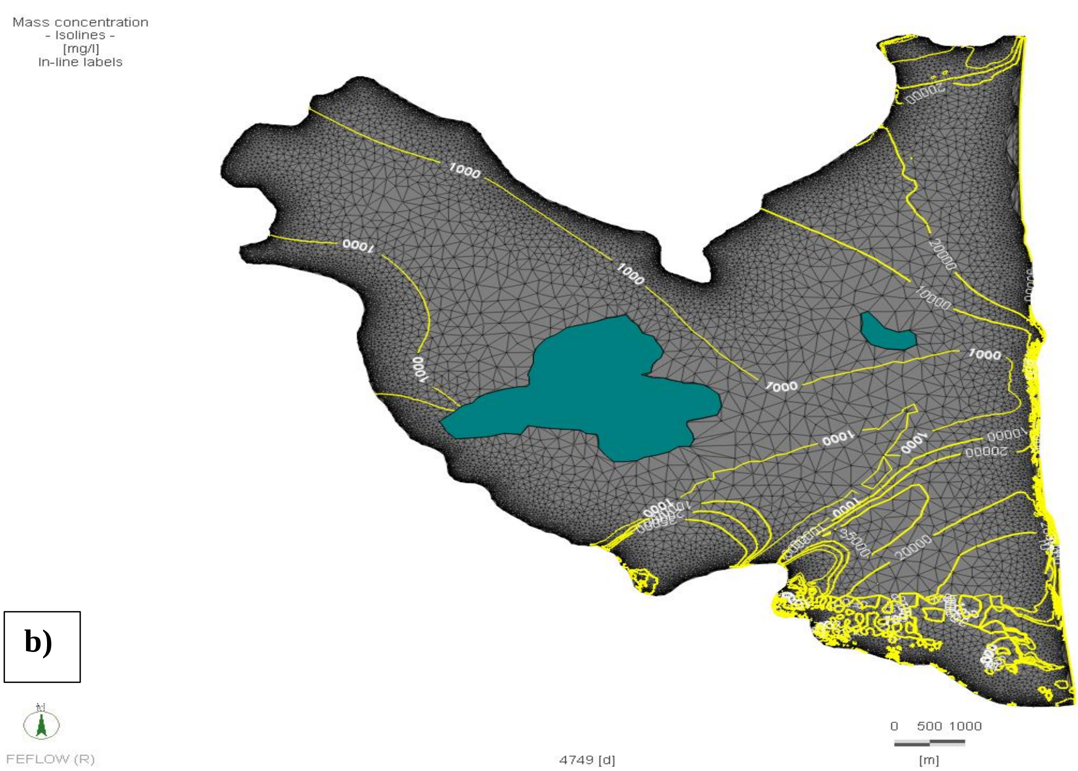


Figure 56*:* Stress period 156-4749 days; a) without pumping, b) with pumping

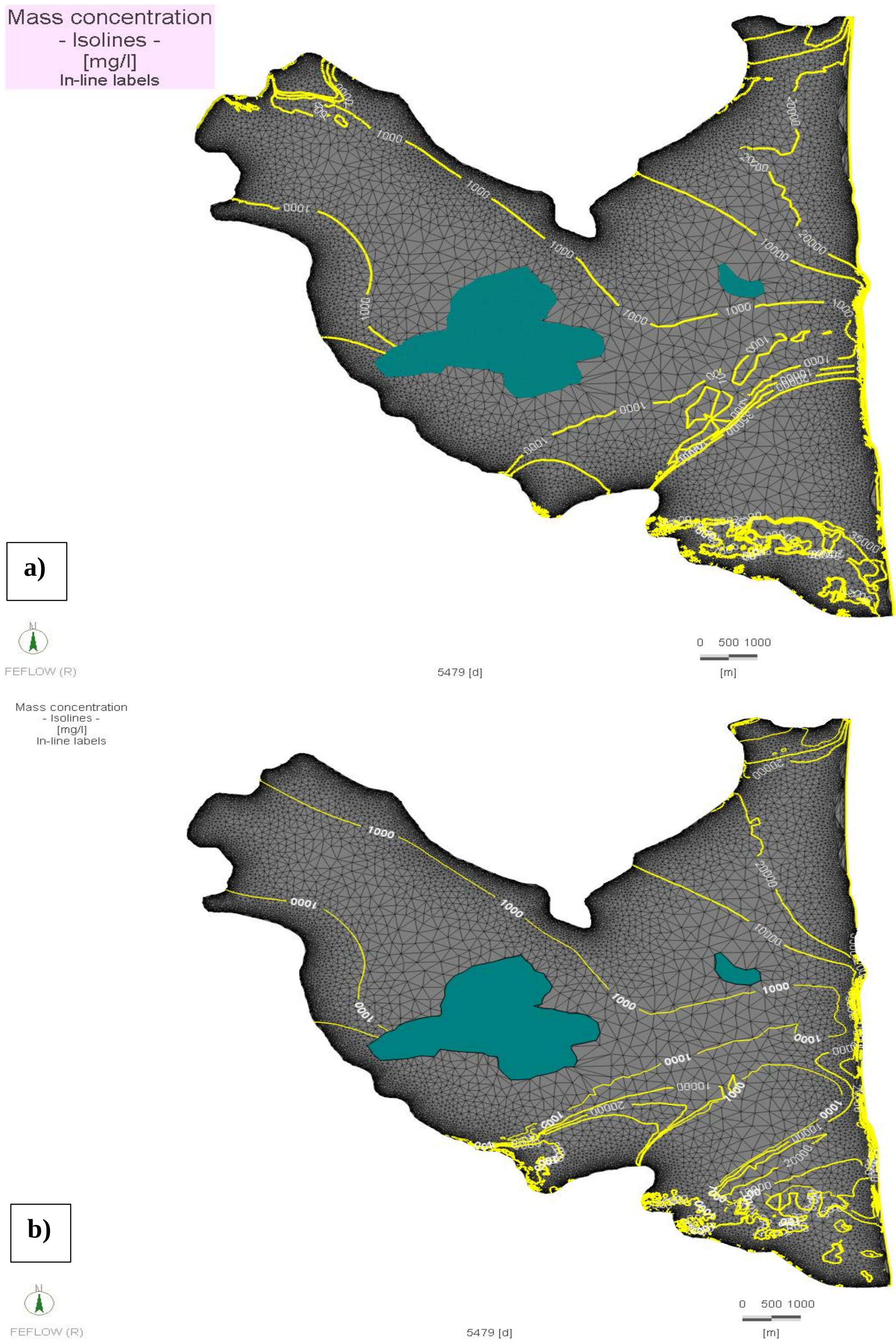


Figure 57: Stress period 180-5479 days; a) without pumping, b) with pumping

6.5.2 Variation in Local Salt Concentration in Groundwater

Variation of local salt concentration in groundwater is shown in Figure 58 from the FEFLOW model and the rest of the figures presented were plotted on excel for better viewing quality. Salt concentration (TDS) range from an initial point of 2087 mg/l and consistently reduced to 600 mg/l under continuous pumping of brackish water from the intrusion zone as shown in Figure 59. Despite a steady decreased of salt concentration in groundwater in well BHF-1, it was not heavily impacted by the pumping scenario due to its location further inland. Well BHF-12 is in the central part of the aquifer and closer to the applied pumping of brackish water or installed wells. Hence the well was heavily impacted in terms of its concentration from an initial concentration of 4176 mg/l to a concentration below 1000 mg/l as shown in Figure 60. Average concentration from initial point is above 30000 mg/l for well BHF-9B, this was reduced to about 1000 mg/l towards the end of the simulation period of 7000 days. Figure 61 showed a steady reduction in concentration as pumping was applied for well BHF-9B. There is a general improvement in groundwater quality in the presented wells.

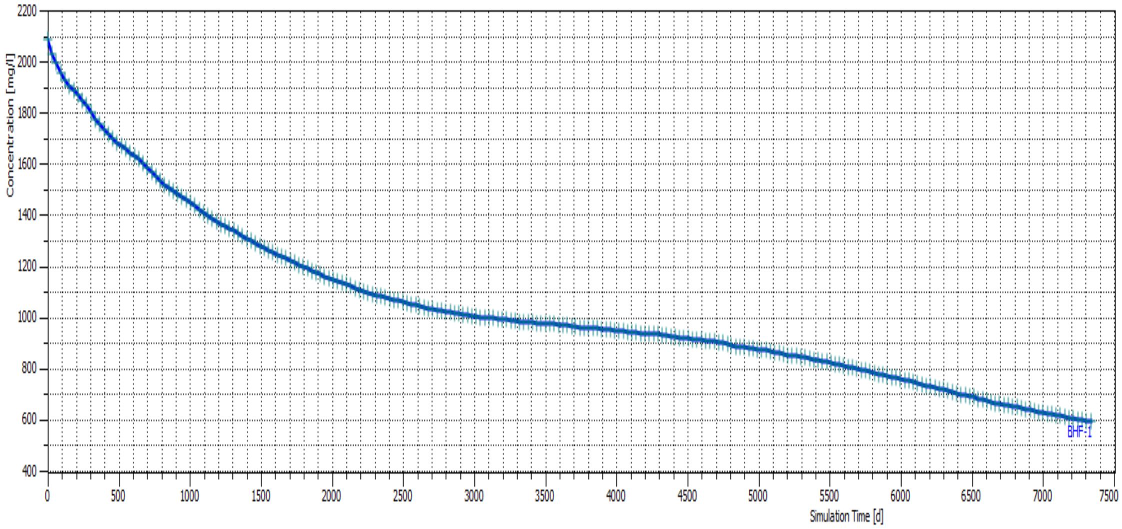


Figure 58: Impacts of pumping brackish water on salt concentration in groundwater well-BHF-1FEFLOW Chart

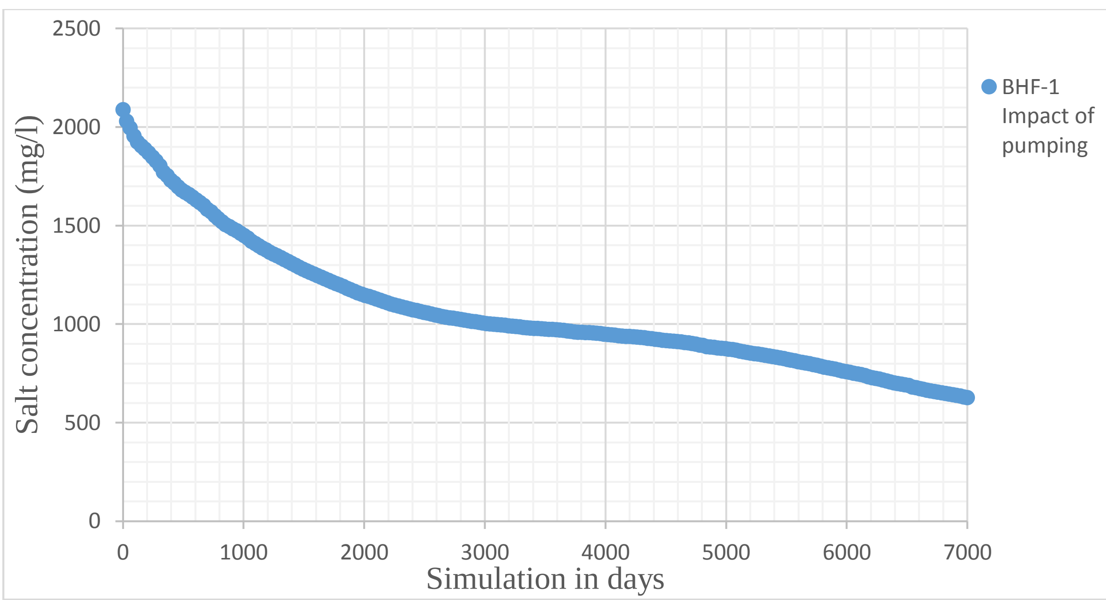


Figure 59: Impacts of pumping brackish water on salt concentration in groundwater well BHF-1

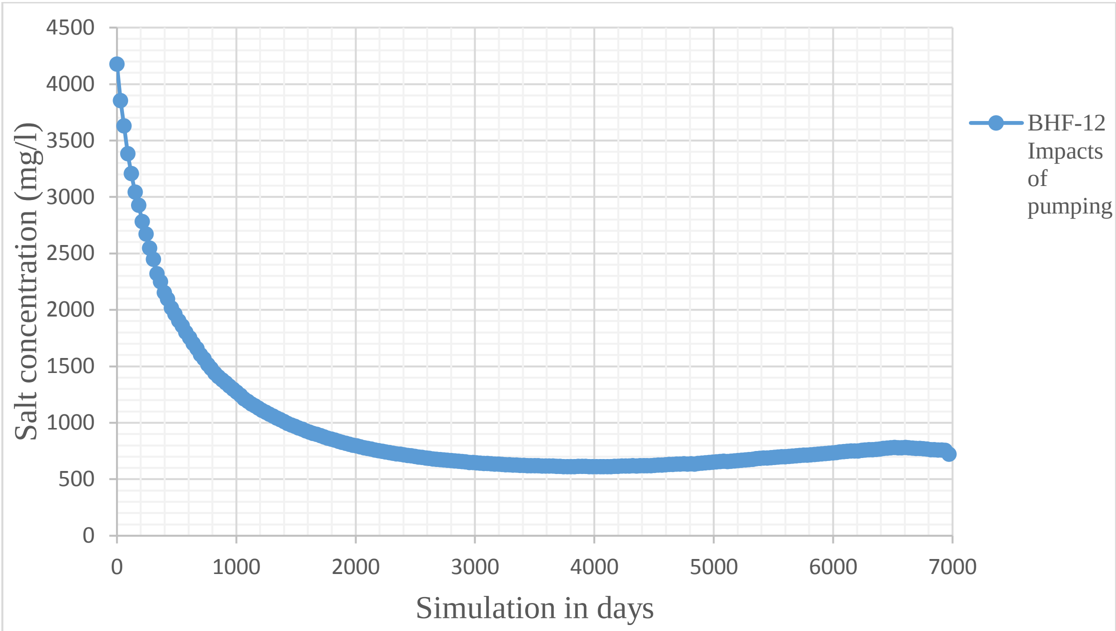


Figure 60: Impacts of pumping brackish water on salt concentration in groundwater well BHF-12

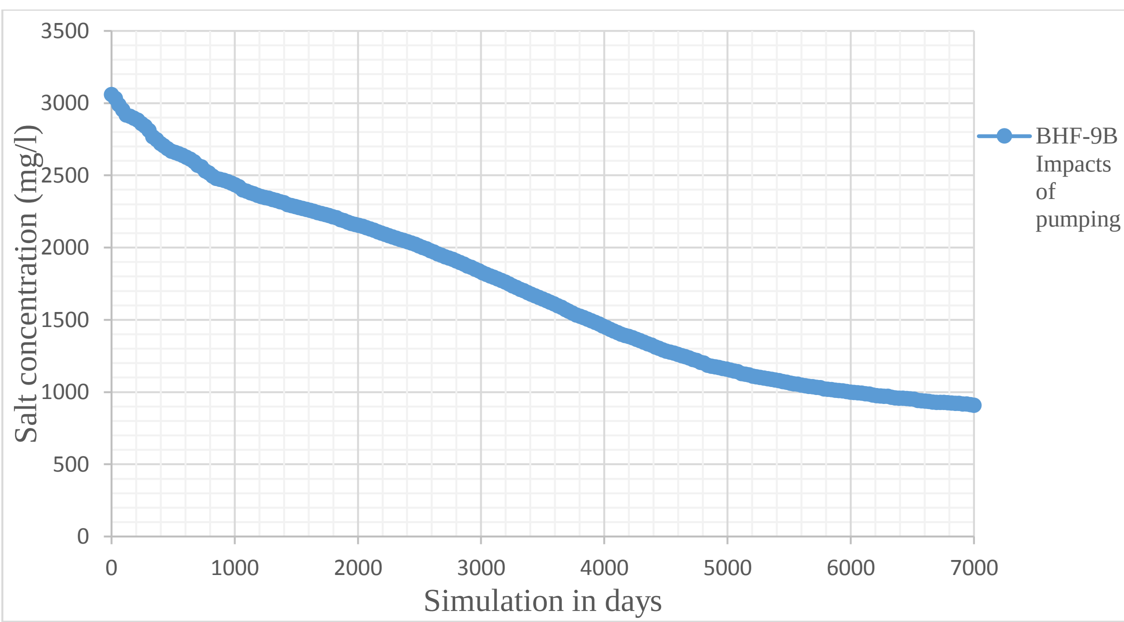


Figure 61: Impacts of pumping brackish water on salt concentration in groundwater well BHF-9B

Chapter 7: Conclusions and Recommendations

There is a serious groundwater level decline in the study area and extensive investigations is required to explore methods to mitigate this problem. The current pumping rate would further lower the groundwater level and can lead to the depletion of groundwater resources before the end of the 21st century. A 5% increase in pumping showed considerable groundwater level decline while a 5% reduction in pumping only showed a minor increase in groundwater level. Pumping of brackish water was showed to have significant impact on the control of seawater intrusion using 16 pumping wells at a discharge rate of 500 m^3/day per well at a distance of 1500 m from the shoreline. This result showed an overall improvement in salt concentration in groundwater distribution.

Seawater intrusion is mostly occurring in the southern eastern part of the aquifer from the shoreline towards inland. Pumping of brackish water showed a reduction in salt concentration in groundwater in the southern eastern part of the aquifer to a maximum level of 20, 000 mg/l while the concentration increase in the non-pumping scenario during the same stress period. Movement of isolines 35, 000 mg/l towards inland was halted after the application of pumping and as such the method could be effective in the control of seawater intrusion in the study area. This technique would improve groundwater quality and could further be exploited to achieve a win-win situation by using the pumped brackish water as feed for nearby desalination plants.

This study recommends an assessment of the cost involve in construction of new pumping wells as well as pipelines or transport vehicles which would be used as desalination plants feed. The study of the most appropriate desalination method most suited for the location and water quality in the area is also be recommended.

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