ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Abdullahi Ali SAID

MODELING OF SEAWATER INTRUSION IN THE COASTAL AQUIFER: A CASE STUDY OF BOSASO PLAIN IN SOMALIA

DEPARTMENT OF CIVIL ENGINEERING

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We certify that the thesis titled above was reviewed and approved for the award of degree of the Master of Science by the board of jury on 19/07/2019.

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ABSTRACT

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Seawater intrusion is process that damage groundwater quality in the coastal regions. Groundwater overexploitation in the Bosaso Plain has resulted in seawater intrusion problem. Groundwater modelling were considered to study the effects of possible seawater intrusion into the Bosaso Plain. In this study, we present a three-dimensional variable–density numerical model developed with the SEAWAT code, which is aimed to predict the extent of seawater intrusion by different groundwater pumping scenarios. Results revealed the higher concentration of electrical conductivity (EC), total dissolved solids (TDS), chloride, sodium, calcium and magnesium along the coastal area which indicated the presence of seawater intrusion in the study area. The SEAWAT model was calibrated using both the average value of heads and TDS concentration for the 2013 field data. Four scenarios were simulated to understand the effects of pumping and climate change to the extent of seawater intrusion for a period of 27 years. The model results show that seawater intrusion significantly affects the groundwater concentrations near the coastline and demonstrated high levels of TDS. The predicted results reveal that increasing pump rate seawater intrusion interface will move about 6.2 km inland by 2040. Results also revealed that a 50% reduction in the pump rate will bring relief to the aquifer by protecting fresh groundwater and preventing any further seawater intrusion.

Key Words: Groundwater modeling, seawater intrusion; coastal aquifer, SEAWAT Bosaso Plain, Somalia.

ÖZ

YÜKSEK LİSANS TEZİ

KIYI AKİFERİNE DENİZ SUYU GİRİŞİMİ MODELİ: SOMALİ 'DE BOSASO OVASI ÖRNEĞİ

Abdullahi Ali SAID

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Deniz suyu girişimi kıyı bölgelerindeki yeraltı suyu kalitesine zarar veren önemli süreçlerden biridir. Bosaso Ovası'nda yeraltı suyunun aşırı çekimi deniz suyu girişimine neden olmaktadır. Yeraltı suyu modelleme çalışması ile Bosaso Ovası'na muhtemel deniz suyu girişimi etkileri çalışma konusu olarak alınmıştır. Bu araştırmada, SEAWAT yazılımı kullanarak farklı senaryoların deniz suyu girişimi üzerindeki etkilerini araştırmak amacıyla deniz suyu girişiminin potansiyel etkisini modellemektir. Analiz sonuçları, kıyı alanı boyunca elektriksel iletkenlik (EC), toplam çözünmüş katı madde (TDS), klorür, sodyum, kalsiyum ve magnezyum konsantrasyonunun yüksekliği ile çalışma alanında deniz suyu girişiminin bulunduğunu ortaya koymaktadır. Model 2013 yılı arazi verileri ile yeraltı suyu seviye ve TDS ortalama değeri kullanılarak kalibre edilmiştir. Yeraltısuyu çekim ve iklim değişikliğinin etkilerini araştırmak için dört farklı senaryo simüle edilmiştir. Sonuçlar, deniz suyu girişiminin sahil şeridine yakın yerlerde yüksek TDS seviyeleri ile yeraltı suyu konsantrasyonlarını önemli ölçüde etkilediğini göstermiştir. Artan yeraltısuyu çekim oranı deniz suyu girişimi arayüzünün 2040 yılına kadar yaklaşık 6,2 km kıyıdan içerilere doğru hareket edeceğini göstermiştir. Ayrıca, çekim oranındaki % 50'lik bir azalmanın, tatlı yeraltı suyunu koruyarak ve daha fazla deniz suyunun sızmasını önleyerek akiferlere rahatlama getireceğini ortaya koymuştur.

Anahtar Kelimeler: Yeraltı suyu modellemesi, deniz suyu girişimi, kıyı akiferi, SEAWAT, Bosaso Plain, Somalia

EXTENDED ABSTRACT

Groundwater is the main sources of drinking water in most global population. In Somalia, most people depend on groundwater as their major source of water. Groundwater models are often the only practical tool used to figure out the behavior and potential response of a groundwater system to future stresses. One of the main advantage applications of groundwater models is to predict the future stresses of aquifers, such as changes in recharge rates resulting from development, the impact of higher groundwater pumping rates or the installation of groundwater remediation systems.

Seawater intrusion is lateral movement of seawater into freshwater aquifer due to the difference between the densities of freshwater and seawater. Seawater intrusion is one of the processes that damage the quality of groundwater in the coastal zones by raising salinity levels where water become unsuitable for drinking and irrigation water. Groundwater Salinization is considered to be one a key pollution source in the coastal aquifers. The seawater intrusion is an unavoidable process that takes place over a long period of time due to natural conditions or man-made such as overexploitation of coastal aquifers. Uninterrupted coastal systems are normally less vulnerable to this phenomenon. Seawater Intrusion is accelerating by over pumping activities. The problem is usually not recognized at the time it occurs.

Coastal plains characterize the most populated areas of the world and depend on groundwater as their main source for water. Seawater intrusion is one of the most important processes that damage the quality of groundwater in the coastal zones. The global population growth and increasing living standards have increased the demand for water. Extreme pumping in the coastal areas has led to a dramatic increase in seawater intrusion problems. Somalia is located in the horn of Africa and its coastline is more than 3333 kilometers in length, the longest of coastline in Africa and the Middle East. The Bosaso is the largest city in the Puntland state of Somalia with its population increasing very fast. The intensive abstraction from coastal aquifers

causes severe seawater intrusion. Thus, the need arises to clearly understand and estimate the extent the seawater intrusion into Bosaso Plain. Hydrochemical analysis and groundwater modeling were considered to study the effects of possible seawater intrusion into the Bosaso Plain.

The main objective of this research is to model the potential effect of seawater intrusion into the coastal aquifer in Bosaso Plain by investigating the effects of different scenarios of pumping on the extend of seawater intrusion by utilizing the SEAWAT, which is a variable density solute transport computer code.

The hydrochemical groundwater analysis results revealed the concentration of electrical conductivity (EC) values of groundwater samples was found to be higher than 1.5 dS/m except for three samples, and groundwater are classified as saline water. The Spatial distribution map revealed the EC concertation is increased from South-east inland to the North coastline of the study area. This substantial rises in EC values shoreward may be a clear indication of seawater intrusion into coastal aquifers of the Bosaso Plain. While, the total dissolved solids (TDS) values o in groundwater in study area vary from 1035.31 mg/l to 10,083.5 mg/l, revealing the very high and dominant salinization problems in some specific locations in the study area mostly area near the shore. In conclusion higher concentration of EC, TDS, chloride, sodium, calcium and magnesium along the coastal area may be a clear indication of the presence of seawater intrusion in the study area.

In this study, we utilized Visual MODFLOW Flex which is graphical user interface for MODFLOW to model groundwater flow and simulate the seawater intrusion. Firstly, to define Conceptual model the base map of the study area was imported into the model. The Digital Elevation Model (DEM) for the top surface of the model obtained directly from SRTM (NASA Shuttle Radar Topography Mission) with 30m-resolution was assigned as the top elevation of the model. The bottom elevation of the aquifer was assigned by interpolating the depth of wells. Since the bottom layer of the aquifer is an impermeable one-layer model of alluvial material (sand and gravel) was considered then the aquifer structural zone was generated. A finite difference grid consisting 1 layer, 92 rows and 107 columns was generated in the study area and each cell contains 10000 m^2 in the horizontal plane. The total active model area covers 48.25 km^2.

Secondly, the model boundary conditions of eastern and western along were assumed to be no flow boundary conditions. Constant head boundary conditions were assigned as a head that does not vary throughout the simulation. For this model, all nodes along the northern side representing the shoreline of the Gulf of Aden (6.5 km) were assigned to a constant head (Dirichlet boundary) condition with 0.0 m elevation and constant concentration with TDS of 35000 mg/l. Afterward, the recharge 85000 m^3/day was assigned along the mountain front in the south of the plain, which applies specified flux stresses to the aquifer system. Then, a total discharge rate of 8000 m^3/day was distributed equally to all 14 production wells in the model. Hence, it assigned as WELL with negative sign to simulate as discharge well.

Model calibration is the process to adjust the model's input parameters in order to match the reality of field conditions to attain the best representation of the aquifer system under certain acceptable criteria. The calibration of steady state simulation was carried by using automated parameter estimation code (PEST). The average static water level and concentration measured in 2013 were taken as the target of steady state calibration. Hydraulic conductivity values estimated by pumping test results was used as the initial values for steady state calibration. The hydraulic conductivity values were adjusted by sequential trial and error runs for all the zones until the reasonable match between the observed and simulated heads was obtained. The model calibration is evaluated by using error statistics criteria such as Mean Error (ME), Mean Absolute Error (MAE) and root mean square (RMS).

The root mean square (RMS) and the determination coefficient (r^2) error between observed and simulated heads, were used to evaluate how the observed values compared to the model simulated targets. The model calibration can be accepted as good match when RMS less than 10 % and r^2 is greater than 0.6. After the completion of steady state of head calibration, RMS of 7.6 % m and r^2 of 0.97 m were achieved, which shows a good match between the observed and calculated heads. While the concertation calibration, RMS of 2.64 % and r^2 of 0.99 % were obtained which indicated a good match between the observed and simulated head. The model does not need any further calibration and is ready for future prediction simulation.

The calibrated SEAWAT model was used to predict various management scenarios to identify the effects of excessive groundwater withdrawal from the coastal aquifer. The recharge rate has been taken in all scenarios as it was in 2013 except in 4^{th} scenario where climate change effect has been considered. Four different scenarios were carried out to simulate the extent of seawater intrusion in Bosaso plain for the years 2013-2040.

Groundwater which contains TDS up to 1500 mg/l can be considered as freshwater and can be used for water supply. It should be noted that the extent of seawater intrusion in the Bosaso aquifer changes from scenario to scenario. The model result of the first scenario indicate that the concentration is increasing as it approaches the shoreline as expected. When compared to the simulated concentration in 2013 the result indicated that the saline water and brackish water will move further 300 m and 500 m inland respectively in 2040. In this scenario the seawater intrusion would not reach new wells, but shows gradually increasing of salinities until 2040 if the current extraction rates are maintained.

Predicted model results of the second scenario indicated that the simulated seawater intrusion will continou to spread further inland by reaching two new municipal wells which will make the total of 7 affected municipal wells. The wells were affected by the first scenerio their TDS concentration was increased.For instance, well B3 had TDS concentration 3286 mg/l in the first scenario and an increased 3377 mg/l in the second scenerio. Furthermore, the width of saline water was moved from 500 m to 700 m where the width of brackish water moved from 5700 m to 6200 m from 2013 to 2040, respectively. The results of the third scenario when climate change effect was considered the model results revealed nomial change in the extent of seawater intrusion.The results of the fourth scenario, by reduced 50 % pumping rate shows slow progress of goundwater qaulity recovery. The predicted results revelad that the two wells will become freshwater. It is evident that increased pumping rate will lead to further seawater movement into Bosaso Plain aquifer.

Based on the findings the study is recommended to be closed all wells located in the contaminated area to avoid further seawater intrusion and to find additional water resource to meet future water demand as increasing water demand leads deterioration of groundwater quality.

GENİŞLETİLMİŞ ÖZET

Yeraltı suyu çoğu küresel nüfusun ana içme suyu kaynağıdır. Somali 'de halkın en büyük su kaynağı yeraltı suyudur. Yeraltı suyu modelleri genellikle gelecekteki streslere karşı bir yeraltı suyu sisteminin davranışını ve potansiyel tepkisini anlamak için kullanılan tek pratik araçtır. Yeraltı suyu modellerinin ana avantajlarından biri, gelişmeden kaynaklanan besleme oranlarındaki değişimler, yüksek yeraltı suyu çekim oranlarının etkisi veya yeraltı suyu iyileştirme sistemlerinin kurulması gibi akiferin gelecekteki gerilimlerini tahmin etmektir.

Deniz suyu girişimi, tatlı su ve deniz suyu yoğunlukları arasındaki fark nedeniyle, deniz suyunun tatlı su akiferine yanal hareketidir. Deniz suyu girişi kıyı bölgelerinde yer altı suyunun kalitesine zarar veren, tuzluluk seviyelerini yükselterek suyun içme ve sulama suyu amacıyla kullanılabilmesini engelleyen bir süreçtir. Yeraltı suyu tuzluluğu kıyı akiferleri için en önemli kirlilik kaynağı olarak kabul edilir. Deniz suyu girişi, doğal koşullar veya aşırı çekimler gibi insan müdahalesiyle, uzun bir süre içinde gerçekleşen kaçınılmaz bir süreçtir Kesintisiz kıyı sistemleri normalde bu olguya daha az hassastır. Deniz suyu girişi aşırı çekim faaliyetleri ile hızlanmaktadır. Sorun genellikle gerçekleştiği zaman fark edilmez.

Kıyı ovaları dünyanın en kalabalık alanlarını karakterize eder ve temel su kaynağı olarak yer altı suyuna bağımlıdır. Deniz suyu girişimi, kıyı bölgelerinde yeraltı suyunun kalitesine zarar veren en önemli süreçlerden biridir. Küresel nüfus artışı ve artan yaşam standartları su talebi artırmaktadır. Kıyı bölgelerinde aşırı çekim deniz suyu girişimi sorunlarını dramatik olarak artırmıştır. Somali, Afrika'nın boynuzunda bulunur ve 3333 kilometrelik kıyı şeridi uzunluğu ile Afrika ve Ortadoğu 'da en uzun sahil şeridine sahiptir. Bosaso, Somali'deki Puntland eyaletinde nüfusu hızla artan büyük şehirdir. Kıyı akiferlerinden aşırı su çekimi, ciddi deniz suyu girişimine neden olur. Bu nedenle, Bosaso Ovası'na deniz suyu girişiminin derecesini açıkça anlama ve tahmin etme ihtiyacı ortaya çıkmaktadır. Hidrokimyasal analiz ve yeraltı suyu modelleme çalışması ile Bosaso Ovası'na mevcut ve muhtemel deniz suyu girişimi etkileri çalışma konusu olarak kabul edilmiştir.

Bu araştırmanın ana amacı, SEAWAT (Değişken Yoğunluklu Sonlu Farklar Yeraltısuyu Akım Modeli bilgisayar kodu) kullanarak farklı su çekim senaryolarının deniz suyu girişimi üzerindeki etkilerini araştırmak amacıyla Bosaso Ovası'ndaki kıyı akiferine deniz suyu girişinin potansiyel etkisini modellemektir.

Hidrokimyasal yeraltı suyu analizi sonuçları ile yeraltı suyu örneklerinin elektriksel iletkenlik (EC) değerlerinin konsantrasyonunun 3 numune dışında 1,5 dS/m den daha yüksek olduğu saptandığından yeraltı suyu, tuzlu su olarak sınıflandırılmıştır. Mekânsal dağılım haritası, EC konsantrasyonunun Güney-Doğu iç kesiminden çalışma alanının kuzey kıyı şeridine doğru artmakta olduğunu göstermiştir. EC konsantrasyon değerlerindeki kıyıya doğru önemli artışlar Bosaso Ovası'nın kıyı akiferlerine deniz suyunun girmesinin açık bir göstergesi olabilir. Çalışma alanındaki yeraltı suyunda toplam çözünmüş katı madde (TDS) değerleri 1035,31 mg/ l ila 10.083,5 mg/l arasında değişirken, çalışma alanında çoğunlukla sahile yakın alandaki bazı çok özel bölgelerde çok yüksek ve baskın tuzlanma problemleri ortaya çıkarmıştır. Sonuç olarak EC, TDS, klorür, sodyum, kalsiyum ve magnezyumun yüksek konsantrasyonu kıyı alanı boyunca çalışma alanında deniz suyu girişiminin varlığı açık bir göstergesi olabilir.

Bu çalışmada, yeraltı suyu akışını modellemek ve deniz suyu girişiminin simülasyonu için MODFLOW kullanan grafiksel kullanıcı arayüzü Visual MODFLOW Flex kullanıldı. İlk olarak, kavramsal modeli tanımlamak için çalışma alanının haritası altlık olarak modele aktarılmıştır. Modelin üst kotu için doğrudan SRTM'den (NASA Shuttle Radar Topography Mission) 30 m çözünürlükle elde edilen Dijital Yükseklik Modeli (DEM), modelin en üst kotu olarak belirlenmiştir. Akiferin alt kotu, kuyu derinliklerinin enterpolasyonu ile belirlenmiştir. Akiferin alt tabakası geçirimsiz olduğu için tek katmanlı alüvyon materyali modeli (kum ve çakıl) kullanıldı ve akifer yapısal bölgesi oluşturulmuştur. Çalışma alanı için 1 katmanlı, 92 sıra ve 107 sütundan oluşan bir sonlu fark ağı oluşturulmuştur ve her bir hücre yatay düzlemde 10000 m^2 dir. Toplam aktif model alanı 48,25 km^2 dir.

İkinci adımda, model sınır koşulları için doğu ve batı boyunca su giriş ve çıkışının (no flow boundary) olmadığı varsayılmıştır. Sabit seviyeli hidrolik yük sınır koşulları, simülasyon boyunca farklılık göstermeyen bir hidrolik yük olarak atanmıştır. Bu model için, Aden Körfezi 'nin (6,5 km) kıyı şeridini temsil eden Kuzey tarafındaki tüm hücrelerde, sabit hidrolik yük (Dirichlet sınırı) 0,0 m yükseklik ve sabit konsantrasyon ise 35000 mg/l TDS olarak atanmıştır. Daha sonra, ova güneyindeki dağ cephesi boyunca akifer sistemine belirlenmiş sabit akış girişi (specified flux stresses) olarak 85000 m^3/gün besleme uygulanmıştır. Daha sonra, modeldeki 14 üretim kuyusuna toplam 8000 m^3/gün çekim oranı eşit olarak dağıtıldı. Kuyulardan çekilen bu değer akiferlerden çekim olduğu için simülasyonda negatif işaretli olarak kullanılmıştır.

Model kalibrasyonu, akifer sisteminin belirli kabul edilebilir kriterler altında gerçek arazi koşullarının en iyi şekilde temsil edilmesini sağlamak için modelin girdi parametrelerini ayarlama işlemidir. Kararlı durum simülasyonunun kalibrasyonu, otomatik parametre tahmin kodu (PEST) kullanılarak yapıldı. Kalibrasyonda gözlenen yeraltı suyu seviye ve TDS değerleri ile model kullanılarak bulunan değerler arasındaki farkı en aza indirgemek hedeflenmiştir. Ortalama statik su seviyesi ve konsantrasyon için 2013 yılında ölçülen değerler kalibrasyonunun hedefi olarak alınmıştır. Pompaj tecrübesi sonuçları ile tahmin edilen hidrolik iletkenlik değerleri, kararlı durum kalibrasyonu için başlangıç değerleri olarak kullanılmıştır. Hidrolik iletkenlik değerleri, gözlenen ve model ile elde edilen yeraltı suyu seviye ve TDS arasında kabul edilebilir bir fark elde edilinceye kadar tüm bölgeler için ardışık deneme-yanılma çalıştırmaları ile ayarlanmıştır. Model kalibrasyonu, ortalama hata (ME), ortalama mutlak hata (MAE) ve kök-ortalama-kare (RMS) hatası gibi hata istatistikleri ölçütlerini kullanarak değerlendirilir.

Gözlemlenen ve model ile elde edilen hidrolik yükler arasındaki ortalama kök-ortalama-kare (RMS) hatası ve determinasyon katsayısı (r^2), gözlenen yüklerle (hedeflerle) model simülasyon hedeflerini kıyaslamasını değerlendirmek için kullanılmıştır. Model kalibrasyonunda kök-ortalama-kare (RMS) hatası % 10 ' dan az, determinasyon katsayısı (r^2) 0,6 değerinden büyükse, kalibrasyonun iyi olduğu kabul edilebilir. Kararlı durum yeraltı suyu hidrolik yük kalibrasyonunun tamamlanmasından sonra RMS, % 7,6 m ve r^2 ise 0,97 olarak elde edilmiştir. Bu sonuçlar gözlenen ve model ile elde edilen hidrolik yük değerleri arasındaki kalibrasyonun çok iyi olduğunu göstermektedir. Konsantrasyon kalibrasyonunda RMS % 2.64, r^2 ise 0.99 olarak elde edilmiştir. Bu sonuçlar da gözlenen ve model ile elde edilen konsantrasyon değerleri arasındaki kalibrasyonun çok iyi olduğunu göstermektedir. Yüksek kalibrasyon değerlerinin elde edilmesi soncunda, modelin daha fazla kalibrasyona ihtiyacı olmadığı ve gelecekteki simulasyon tahminleri için hazır olduğu sonucuna varılmıştır.

Kalibre edilen SEAWAT modeli, kıyı akiferindeki aşırı yeraltı suyu çekim etkilerini belirlemek amacıyla çeşitli yönetim senaryoları tahmin etmek için kullanılmıştır. Besleme oranları, iklim değişikliği etkisinin dikkate alındığı 4. senaryo hariç tüm senaryolarda 2013 yılında olduğu gibi alınmıştır. Bosaso ovasında deniz suyu girişiminin boyutunu simüle etmek için 2013-2040 yılları arasında dört farklı senaryo gerçekleştirilmiştir.

Su temini için 1500 mg/l e kadar TDS içeren yeraltı suyu tatlısu olarak kabul edilebilir ve kullanılabilir. Bosaso akiferindeki deniz suyu girişiminin boyutunun senaryodan senaryoya değişmektedir. İlk senaryonun model sonucu, beklendiği gibi kıyı şeridine yaklaştıkça konsantrasyonun arttığını gösterirmiştir. Simulasyon sonuçlarına göre 2013 yılı ile 2040 yılı konsantrasyonları karşılaştırıldığında tuzlu suyun 300 m, acı suyun (hafif tuzlu su) 500 m kıyıdan iç kısımlara ilerleyeceğini göstermiştir. Bu senaryoda, deniz suyu girişi yeni kuyulara ulaşmayacak, ancak mevcut çekim oranlarının sürdürülmesi halinde 2040 yılına kadar tuzlulukların kademeli olarak artacağını göstermektedir. İkinci senaryo için tahmin edilen model sonuçları, simüle edilmiş deniz suyu girişinin iç kesimler doğru daha fazla yayılmaya devam edeceğini, iki yeni belediye kuyusuna da ulaşarak etkilenen kuyu sayısını 7 ye çıkaracağını göstermiştir. Kuyular ilk senaryodan etkilendikleri için TDS konsantrasyonları artmıştır. Örneğin, B3 kuyusunun ilk senaryoda TDS konsantrasyonu 3286 mg/l iken ikinci senaryoda artarak 3377 mg/l olmuştur. Ayrıca, 2013 yılından 2040 yılana kadar tuzlu su genişliği 500 m'den 700 m'ye; hafif tuzlu su genişliği ise 5700 m'den 6200 m'ye çıkmaktadır. İklim değişikliğinin etkisi göz önüne alındığında üçüncü senaryonun model sonuçları, deniz suyu girişi kapsamındaki nominal değişikliği ortaya koydu. Dördüncü senaryoda % 50 azaltılmış çekim oranına göre model sonuçları, yeraltı suyu kalitesi geri kazanımında yavaş ilerleme olduğunu göstermiştir. Tahmin edilen değerler, iki kuyunun tatlı su olacağını ortaya çıkarmıştır. Çekim oranındaki artışın Bosaso Ovası akiferine deniz suyunun daha fazla girmesine neden olacağı ortaya çıkmıştır.

Çalışma bulgularına göre, daha fazla deniz suyu girişimini önlemek için kirletilmiş alanda bulunan tüm kuyuların kapatılması ve artan su talebi, yeraltı suyu kalitesinin bozulmasına yol açtığından gelecekteki su talebini karşılamak için ek su kaynağı bulunması gereklidir.

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ABBREVIATIONS

DC	: Direct Current
EC	: Electrical Conductivity
TDS	: Total Dissolved Solids
SAR	: Sodium Adsorption Ratio
VES	: Vertical electrical soundings
USGS	: United States Geological Survey
FDM	: Finite Difference Method
FEM	: Finite Element Method
VDF	: Variable Density Flow
MODFLOW	: Modular Finite-Difference Ground-Water Flow Model
MT3D	: Modular Three-dimensional Transport Model
MT3DMS	: Three-Dimensional Multispecies Transport Model
SEAWAT	: Three-Dimensional Variable-Density Groundwater Flow Model
FEFLOW	: Finite Element subsurface FLOW
SIP	: Strongly Implicit Procedure
SOR	: Successive Over Relaxation
PCG	: Preconditioned Conjugate Gradient
MSL	: Mean Sea Level
MASL	: Above Mean Sea Level
OBS.	: Well Observation Well
PDE	: Partial Differential Equation
PEST	: Non-Linear Parameter Estimator
RMS	: Root Mean Square Error
SRTM	: Shuttle Radar Topography Mission
DEM	: Digital Elevation Model
GIS	: Geographic Information System

UTM	: Universal Transverse Mercator
VMOD	: Visual MODFLOW Flex
WHO	: World Health Organization
MFR	: Mountain front recharge
PSWEN	: Puntland State Agency for Water Energy and Natural Resources
GUMCO	: Golden Utilities Management Company

1. INTRODUCTION

1.1 Background

Water is one of the important elements all are living things. The largest volume of the earth water is surface water and it is estimated at 99.4 %. Groundwater represents about 0.6 % of the total. However, most of the surface water is form in oceans 97 %. Groundwater consists of 22 % of all fresh water on the earth while polar ice is about 77%. The fresh water in the surface that are accessible are lakes 0.3 % and rivers 0.003 % respectively (Bear et al., 1999).

The hydrological cycle consisting of continuous processes as shown in Figure 1.1 which is the central focus of hydrology. The hydrological cycle starts with the water evaporating from the ocean's surface. When humid air is lifted, vapored water is cooled and clouds forms. Humidity is then transported all over the world until it returns as precipitation to the earth's surface. Once the rainwater drops in the ground, a portion of the rainwater might evaporate back into the atmosphere or may infiltrate into the subsurface and become groundwater. Groundwater either discharge into the oceans, rivers, and streams, or is released by transpiration into the atmosphere. The water balance remaining on the surface of the earth is a runoff, which flows into rivers, streams and lakes returns to the oceans, where the water cycle starts again.

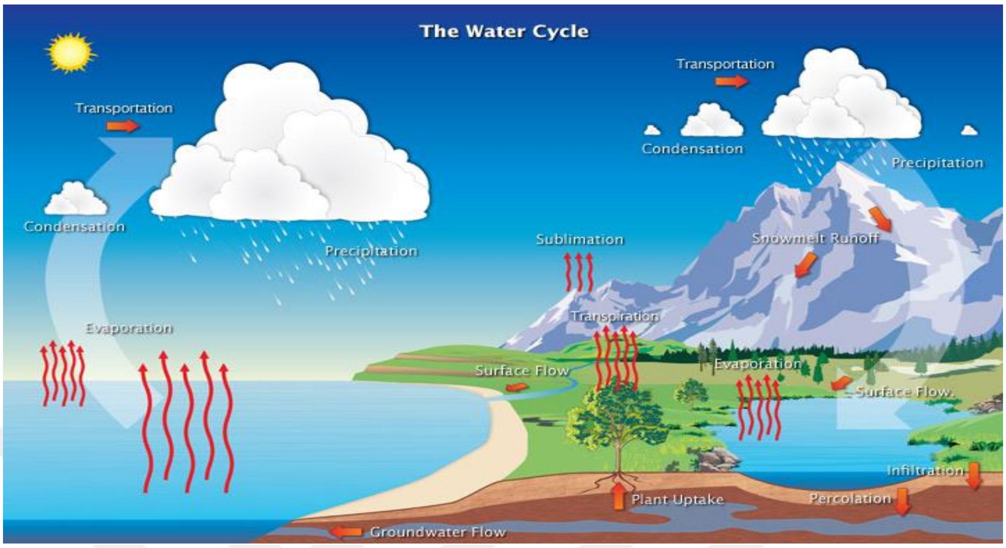


Figure 1.1. Diagram of hydrologic cycle (https://pmm.nasa.gov/education/water-cycle/hydrologic-cycle)

Groundwater is one component of the hydrologic cycle and it is water flows or sinks subsurface and saturates soil or rock, supplying springs and wells. Groundwater often starts as rainfall penetrates into the soil where underground spaces and pores are stored this geological material are called aquifers. The water table is the top surface of the saturated layer. More than 98 % of the available fresh water is groundwater (Fette, 2001). Groundwater is one of the world's main sources of drinking water (Bear, 1979).

In Somalia, most people depend on groundwater as their major source of water. Except for the people who live along the rivers Juba and Shabelle, who also use surface water to satisfy their water requirements, groundwater from shallow wells, boreholes and springs is the primary water sources of most of the country's population. Groundwater is used by rural and urban populations to satisfy the needs of domestic and livestock water and small - scale irrigation. (Basnyat, 2007). Groundwater quality monitoring is a key issue in water resources development and management.

Groundwater models are often the only practical tool to figure out the behavior and potential response of a groundwater system to future stresses. One of the main advantage applications of groundwater models is the prediction the future stresses for aquifers, such as changes in recharge rates resulting from development, the impact of higher groundwater pumping rates or the installation of groundwater remediation systems.

Seawater intrusion is one of the processes that damage quality of groundwater in the coastal zones by raising salinity levels where water become unsuitable for drinking and irrigation water. Groundwater Salinization is considered to be one a key pollution sources in the coastal aquifers. The seawater intrusion is an unavoidable process that takes place over a long period of time due to natural conditions and man-made such as overexploitation of coastal aquifers. Seawater intrusion is lateral movement of seawater into freshwater aquifer due to the difference between the densities of freshwater and seawater, freshwater is found above seawater and prevents the upward movement of seawater.

Uninterrupted coastal systems are normally less vulnerable to this phenomenon. Seawater Intrusion is accelerating by over pumping activities. The problem is usually not recognized at the time it occurs. This problem starts to spread out in many areas of the word coastal aquifers such as Palestine (Qahman and Larabi, 2006), Nigeria (Oter and Atolagbe, 2003), Tunisia (Gaaloul et al., 2012) and Turkey (Cobaner et al., 2012). Several methods have been used to control the seawater intrusion in the coastal aquifers and to protect groundwater reserves.

(Todd, 1974) presented different methods to prevent the contamination of seawater intrusion from groundwater sources including: reduction pump rate, relocation of abstraction wells, underground barriers, natural recharge, artificial recharge and abstraction of saltwater.

1.2 Problem Statement

Coastal plains characterize the most populated areas of the word. The coastal aquifers become an important source of water in arid and semi-arid coastal regions. These coastal regions are facing serious hydrological problems for example: freshwater scarcity, groundwater contamination and seawater intrusion. The global population growth and increasing living standards have increased the demand for water. Extreme pumping in the coastal areas has led to a dramatic increase in seawater intrusion problems. Somalia is located in the horn of Africa and its coastline is more than 3333 kilometers in length, the longest of coastline in Africa and the Middle East.

The Bosaso is the biggest city in the Puntland state of Somalia with its population is increasing fast in the early 1990s the town had a population of approximately 10,000 (Norconsult, 1997). Today, the city has population approximately 430,000 this rapid development brings excessive groundwater withdrawal from the coastal aquifer of Bosaso Plain. This intensive abstraction caused degradation of groundwater quality and seawater intrusion problem. Thus, the need arises to clearly understand and estimate the groundwater flow and extend seawater intrusion into the Bosaso coastal aquifer. A numerical model will be used as an effective management tool in order to take appropriate decisions to avoid the further decline of water quality.

1.3 Objectives

The main objective of this research is to model the potential effect of seawater intrusion into the coastal aquifer in Bosaso Plain and to investigate the effects of different sceneries of pumping on seawater intrusion by utilizing the SEAWAT, which is a variable density solute transport computer code. However, the specific objective of the study is the following:

- To investigate seawater intrusion by using geochemical technique.

- Development of a conceptual and numerical model for simulating groundwater flow and seawater intrusion.
- To calibrate the MODFLOW and SEAWAT model using observed data.
- To use the calibrated model to predict future seawater extension by using different management scenario

2. LITERATURE REVIEW

2.1 Introduction of Seawater Intrusion

Seawater intrusion is one of the most concerning processes damages groundwater quality by increasing salinity to above acceptable level of drinking water and irrigation requirements and jeopardizes future groundwater exploitation of the coastal aquifers. Groundwater salinization is considered to be one of the major pollution sources. Groundwater salinization sources of include: infiltration of saline wastes, return flow from irrigation, evapotranspiration and seawater intrusion. Seawater intrusion is a natural process that occurs in most of the coastal aquifers due to the difference in density between fresh water and saltwater (Bear, 1979). Seawater contains about 35,000 mg/l of total dissolved solids. It is therefore obvious that even a small amount of seawater can cause problems with drinking and irrigation water when mixed with fresh water supplies. A mixing of only 1% would triple the groundwater salinity, while 5% would increase salinity to over 1000 mg/l in chloride (Bear, 1999). A contribution of 2% seawater mixed with fresh groundwater would render the water unsuitable for public supply according to USEPA guidelines (Barlow, 2003). Furthermore, in irrigation salinity can be harmful to farming, by reduce yields and destroy crops with low salt tolerance. In some cases, conditions may require changing in salt - tolerant crops. Seawater was also shown to decrease soil erodibility and soil structure (Jenkins and Moore, 1984).

Seawater intrusion, which is a main issue in the coastal aquifers in many parts of the world. Coastal cities are generally most densely populated areas in the world. Almost two third of the world population lives in coastal areas. Most of the coastal regions depend on groundwater as their major source of water supply for domestic, industrial and irrigation uses. Rapid development and increasing population growth and industrialization will increase dramatically the amount of groundwater uses, which brings seawater intrusion problems. The control of seawater intrusion has become the main challenge to water resources management.

Most of the coastal areas all over the world are experience seawater intrusion problems. It may occur due to natural events like climate change and rising sea level and manmade human activities such as extensive pumping. After seawater intrusion takes place in coastal aquifers, the amount of freshwater storage is minimized, leaving a major problem for coastal populations that depend on groundwater as their primary source of freshwater (Masterson, 2004).

The main causes of seawater intrusion include (Bear et al., 1999):

- Over- exploitation of the aquifers
- Seasonal fluctuations of groundwater level
- Tidal effects
- Barometric pressure
- Seismic waves
- Dispersion
- Climate change and rising sea level

Overexploitation is the main causes of seawater intrusion. Salinization is one of the world's most common forms of groundwater pollution. Seawater intrusion causes a key limitation of groundwater resources sustainability. Coastal aquifers should be better managed in order to control the seawater intrusion and to protect groundwater resources from contamination. In order to prevent and control seawater intrusion and to find out the starting period of seawater intrusion, follow up it is revolution and it is extending numerical modelling should be adopted.

2.2 Seawater Intrusion Investigation Methods

To understand Seawater intrusion in coastal regions information on the geological and hydro-chemical characteristics of aquifers is required. In hydrology studies, understanding the movement mechanisms between fresh and seawater interface is an important issue. Therefore, several methods, including geophysical, geochemical, analytical and numerical models, have been developed to determine the interface position of the freshwater and seawater and to simulate changes in future salinity water and levels. The following sections provide a short description of the common methods.

2.2.1 Geophysical Investigations

Geophysical investigations involve taking measurements at subsurface that are influenced by the internal distribution of physical properties. Analysis of these measurements can show how the physical properties of the subsurface vary vertically and laterally. Geophysical methods measure the spatial distribution of physical properties the earth's, such as bulk conductivity or seismic velocity. A substitute method of investigating subsurface geology is, by of borehole drilling, but this method is costly and provides information only at discrete locations. These physical characteristics can be linked to hydrological or geological features, such as water quality distribution or the geometry, position, (Bear et al., 1999). Geophysical methods can be classified as follows:

2.2.1.1 Subsurface Geophysical Methods

- Electrical methods, such as: DC resistivity, frequency domain electromagnetic methods, airborne EM, loop-loop EM, time-domain electromagnetic sounding, and very low frequency EM
- Seismic methods, such as seismic reflection and seismic refraction
- Ground penetrating radar

2.2.1.2 Borehole Methods

- Electric logs

- Radiometric logs
- Integrated use of borehole logs

2.2.1.3 Integrated Geophysical Surveys

In recent years, many researchers used geophysical methods to investigate seawater intrusion. (Adeoti, 2010) Have conducted integrated geophysical approach of electrical resistivity and induced polarization methods to investigate seawater intrusion in Nigeria. The results of 1D and 2D correspond to a very high degree of seawater intrusion between depth interval of 13 m and 64 m in the aquifer. Two main freshwater aquifers (shallow < 6 m and deep > 60 m) where defined with most of them occurring unprotected area**.** (Shaaban, 2001) has used Vertical electrical soundings (VES) to evaluate hydrogeological characteristics of the subsurface in a coastal area of northwestern Egypt. The results revealed Shallow brackish to fresh water bearing limestone aquifer of Pleistocene age and a deep saline water bearing sandy limestone of Miocene age.

2.2.2 Geochemical Investigations

Geochemical techniques are used throughout the world coastal aquifers to identify the occurrence of seawater intrusion and to identify the source of salinity. The Use of geochemical analysis in seawater intrusion studies requires a good characterization of the hydrogeological, hydraulic properties, and physical boundaries of the aquifer, the distribution of groundwater levels and groundwater withdrawal locations in the aquifer (Reilly, 1993). Therefore, the distinction of different salinization mechanisms is essential to the evolution of the origin, pathways, rates and future salinization of coastal aquifers. The origin of salinity in coastal aquifers can be classified using several geochemical criteria as given below (Bear et al., 1999).

- Electrical Conductivity (EC) and Total Dissolved Solids (TDS) concentration are most frequently used criteria to investigate seawater intrusion
- Chloride concentration: 200 mg/l of chloride concentration in groundwater is used as index of Seawater intrusion.
- Cl/Br ratios: the bromide ion can be considered as a good indicator of seawater Intrusion. The bromide concentration of in fresh water is less than 0.01 mgl^{-1}.
- Na/Cl ratios
- Ca/Mg, Ca/(HCO3+SO4) ratios
- O and H isotopes
- Boron isotopes

Recently, many coastal aquifers around the world, geochemical studies have been conducted to classify salinity and its source. For instance (Hiroshiro et al., 2006) conducted a geochemical investigation to examined recent increases salinity in groundwater for the in Fukuoka, Japan. Result revealed a strong increase in electrical conductivity at 15–20 m depth, matching to the freshwater and saltwater interface. In addition, results indicated that the aquifer was originally below the current sea floor and that deeper saline groundwater is not mixed with the shallower fresh groundwater. The overall results revealed that the deeper groundwater is influenced by seawater intrusion. (Edet and Okereke, 2001) investigate the extent of seawater intrusion using hydro-chemical data and vertical electrical sounding into shallow aquifers beneath the coastal plains of southeastern Nigeria. The study concluded that saltwater contamination is a feature of island locations at depths greater than about 20 m.

2.2.3 Mathematical Methods

Groundwater modeling is a demonstration of the reality of an aquifer system. Modelling Groundwater has become a key process in monitoring and managing groundwater resources. Over the past years, numerical models were established in order to understand the groundwater flow and mechanism of seawater intrusion process in coastal aquifers. Numerical models are based on mathematical models which derived from Darcy's law and the law of conservation of mass. The accuracy of model predictions depends on the reliability of the estimated model parameters and the accuracy of the boundary conditions (Todd and Mays, 1980).

Numerical models were developed to solve the groundwater flow equations in combination with solute transport by using Finite Element Method Finite (FEM) or Difference Method (FDM) or a combination of these. However, it will be difficult to develop and solve groundwater flow and solute transport more than groundwater flow alone. In coastal aquifers, water density and chemical concentration may vary across the model area, making it difficult to simulate the aquifer numerically. Two approaches have been used to simplify this problem: the first is to assume that both freshwater and seawater are immiscible and separated by a sharp interface, the second is to consider that freshwater and seawater are single fluids and have a spatially variable concentration of salt that affecting the density of fluid; this approach is the principle of density dependent groundwater flow and solute transport modelling. Several computer codes that have been developed by researchers are used to solve groundwater flow and solute transport problems (Bear and Cheng, 2010).

2.3 Numerical Methods of Groundwater Modelling

Groundwater modelling has become an important tool for groundwater resources monitoring, quality assessment and managing. Groundwater modelling is considered to be an excellent way of presenting the hydrogeological situation of the groundwater system and predicting future scenarios of groundwater withdrawal and their effect of socio-economic impacts (Himmelsbach and Buter, 2001). The groundwater flow with combination solute transport models can be used to assess the effect of current or future activities on groundwater quantity and quality (Istok, 1989). Groundwater Models are a visualization of reality of aquifer to investigate certain situation or to predict the future behavior of a certain system. Numerical models are mathematical models that use the numerical time-stepping procedure to solve the groundwater flow equations with combination solute transport over time. In contrast to analytical solutions, numerical solution the head is calculated at discrete points (nodes) and is not continuous in space or time. Finite Difference Method (FDM) and Finite Element Method (FEM) are the most common methods used in groundwater modelling.

2.3.1 Governing Equation for Groundwater Flow

The governing equation derived below is the most commonly used in modelling of groundwater flow. It represents Darcy's law, the flow of a single-phase fluid (water) in a continuous porous medium at constant density. The general governing equation (differential equation) representing three-dimensional transient groundwater flow for heterogeneous and anisotropic conditions are given below

$$\frac{\partial}{\partial_x}(k_x\frac{\partial h}{\partial x}) + \frac{\partial}{\partial_y}(k_y\frac{\partial h}{\partial y}) + \frac{\partial}{\partial_z}(k_z\frac{\partial h}{\partial z}) = S_s\frac{\partial}{\partial_t} - W \quad (2.1)$$

Where k_x ,k_y, k_z area the hydraulic conductivity of three principal of flow x, y and z and $\frac{\partial h}{\partial x}$, $\frac{\partial h}{\partial y}$, $\frac{\partial h}{\partial z}$ are components of vector grad h, is hydraulic head S_s, specific storage W, is sources and sinks. For steady state conditions water following into the system is equal water following out to the system and equation (2.1) is equal zero. Equation (2.1) is used in most groundwater numerical flow codes (Anderson et al., 2015).

2.3.2 Finite Difference Method

Finite difference methods (FDM) is one of the oldest methods for solving differential equations. By utilizing the finite difference model, groundwater levels or solute transport are calculated as discrete values at the grid nodes, or at the center points of cells (Spitz and Moreno, 1996). One of the main disadvantages of FDM is that it cannot represent the irregular boundary of the continuous medium.

The first step of solving groundwater flow or solute transport problem by FDM is to discretize the problem. As shown in Figure 2.1 discrete aquifer system where I, j, k represents columns, rows and layer. The spacing of nodes along rows is designated by Δ_x and the spacing along columns by Δ_y, while the spacing between layers isΔ_z . The node is situated within an FD cell or block (Fig. 1b, c). Heads are defined only at nodes and the head at a node represents the average head in the FDM cell/block. An approximate form of the governing equation is written by replacing the partial derivatives in Equation 2.1 by differences.

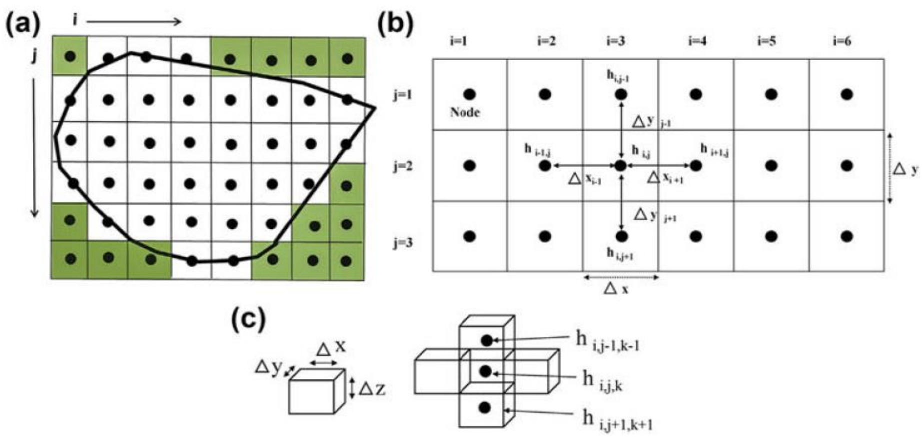


Figure 2.1. Finite-difference (FD). (a) Two-dimensional Finite-difference grid (b) 2D horizontal FD grid with notation of five nodes comprising the FD (c) Three-dimensional notation (Anderson et al., 2015)

2.3.3 Governing Equation for Solute Transport

The attention in understanding the mechanism and prediction of solute transport through groundwater has increased in the last decades due to growing subsurface pollution. The dissolved substances in water are called solutes, Groundwater contains dissolved solutes like dissolved minerals, salts, metals. The important physical processes controlling the transport of non-reactive contaminants in the aquifer are advection and dispersion that create a spreading pollution plume and cause dilution in the pollutant concentration. Advection transport is the movement of solute by the bulk movement of groundwater, the movement of particles within flowing water. The velocity of the bulk movement of groundwater is the average linear velocity of groundwater. While dispersion occurs when contaminated mixes with groundwater and solutes transported by the random thermal motion of solute molecules.

The transport of solute contaminants in groundwater can be described by partial differential equation for three dimensional (Zheng and Bennett, 1995)

$$\frac{\partial c}{\partial_t}(k_x \frac{\partial}{\partial x_i}) + (D_{ij} \frac{\partial c}{\partial x_j}) - \frac{\partial}{\partial x_i}(v_i C\ ) + \frac{q_s}{\theta}(c_s) + \sum_{k=1}^{N} R_k \qquad (2.2)$$

Where, C is the contaminant concentration dissolved in groundwater, t is the time, x_i is the distance along the respective Cartesian coordinate axis D_{ij} is the hydrodynamic dispersion coefficient, v_i is the seepage or linear pore velocity, q_s is the volumetric flux of water per unit volume of aquifer representing sources (positive) and sinks (negative), c_s is the concentration of sources or sinks, θ is the porosity of the porous medium, and, R_k is the chemical reaction term.

2.3.4 Governing Equation for Variable Density Flow (VDF)

All groundwater contains some extent of dissolved material such as salts, metals and minerals. They are typically present in relatively low concentrations so that they do not have a significant impact on water density. However, the concentration of dissolved components in water can significantly affect its density in coastal areas where fresh groundwater can come into contact with seawater. Even relatively small density increases, such as when moving from fresh water (around 1000 kg/m^3) to saltwater (around 1025 kg/m^3), have shown a significant impact on groundwater flow patterns and rates (Guo and Langevin, 2002). Since equation 2.1 used in Modflow is based on constant density, therefore the effect of density dependent flow must be considered.

Guo and Langevin (2002) derive the governing equation for variable density groundwater flow in terms of the freshwater head, as used in SEAWAT code as follows:

$$\frac{\partial}{\partial\alpha}\left(\rho k_{f\alpha}\left[\frac{\partial h_f}{\partial\alpha}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial\alpha}\right]\right)+\frac{\partial}{\partial\beta}\left(\rho k_{f\beta}\left[\frac{\partial h_f}{\partial\beta}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial\beta}\right]\right)+\frac{\partial}{\partial\gamma}\left(\rho k_{f\gamma}\left[\frac{\partial h_f}{\partial\gamma}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial\gamma}\right]\right)=\rho S_f\frac{\partial h_f}{\partial t}+\theta\frac{\partial\rho}{\partial C}\frac{\partial C}{\partial t}-\bar{\rho}q_s \tag{2.3}$$

Where Where α, β, γ are orthogonal co - ordinate axes, aligned with the main directions of permeability; Kfα, Kfβ, Kfα are three - dimensional hydraulic conductivities; h_f is the equivalent freshwater head; ff is the freshwater density; Z is elevation of the measurement point above some datum, S_f is the equivalent freshwater specific storage; $\bar{\rho}$ is the density of water that enters or leaves through source or sink; $q_s$is the volumetric flow rate of sources or sinks per unit volume of aquifer; C is the dissolved concentration of contaminates in groundwater; t is the time

SEAWAT uses the MT3DMS computer program to solve the solute transport equation (2.2). Baxter and Wallace (1916) have developed an empirical relationship between seawater density and concentration, to convert solute concentration to fluid density as follows:

$$\rho = \rho_f + EC \tag{2.4}$$

where: E is a density vs. concentration slope having constant value of 0.7143 for salt concentrations ranging from zero to that of seawater, and C is the concentration of salt [M/L^3].

2.3.5 Sharp Interface

In coastal aquifers, fresh groundwater discharges to the ocean along with the freshwater-seawater interface as shown in the Figure 2.2. The modelling of seawater intrusion is a complicated problem because the intrusion process can vary from one aquifer to another. A common approach of seawater intrusion modelling is based on the sharp interface and the Ghyben– Herzberg relation. (Badon Ghyben, 1889; Herzberg, 1901) studied the location of the fresh and saltwater interface in a coastal homogeneous, isotropic unconfined aquifer based on piezometric heads. They assumed that freshwater and seawater are immiscible and separated by a sharp interface. This relationship is due to static conditions; however, the interface is not static in Field condition and can moves in the response of pumping, changes in recharge, tidal fluctuations (Anderson et al. 2015). Here are some researchers who used the sharp interface assumption to evaluate seawater intrusion (Hubbert, 1940; Henry, 1959; Glover, 1959 and Kacimov et al., 2006)

Figure 2.2 shows the interface between both freshwater and seawater zones. Freshwater flow towards the sea and seawater flows towards the freshwater aquifer. The position of the fresh-seawater interface can be influenced by the change in groundwater level according to the Ghyben-Herzberg principle.

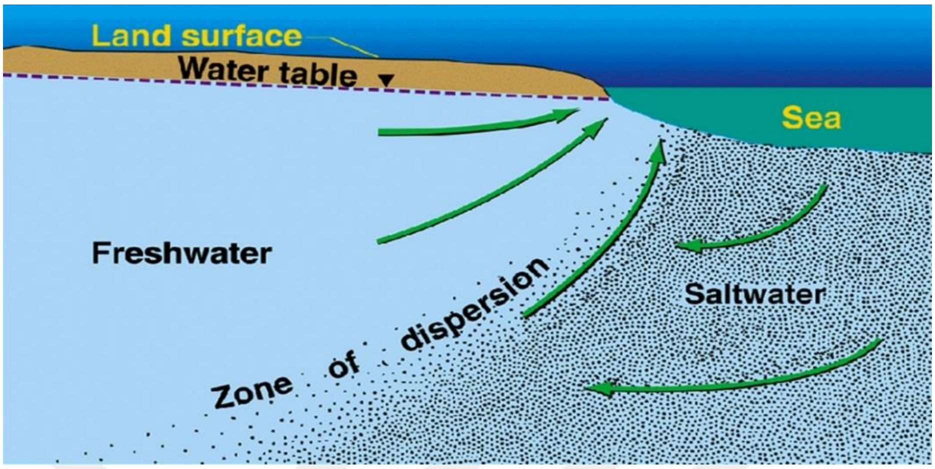


Figure 2.2. Freshwater and seawater interface in a coastal aquifer (Barlow, 2003)

Ghyben-Herzberg principle states that:

$$z = \frac{\rho_f}{\rho_s - \rho_f} h \quad (2.5)$$

Where z is the height seawater column, ρ_f is density of freshwater ρ_s is density of seawater, h is t hydraulic head above sea level. Generally, the freshwater and seawater densities are 1000 kg/m^3 and 1025 kg/m^3, respectively. Therefore, Equation (2.5) can be modified as;

$$z = 40h \quad (2.6)$$

The depth to the interface between freshwater and seawater is approximately 40 times the height of the water table above mean sea level as shown in the Figure 2.3.

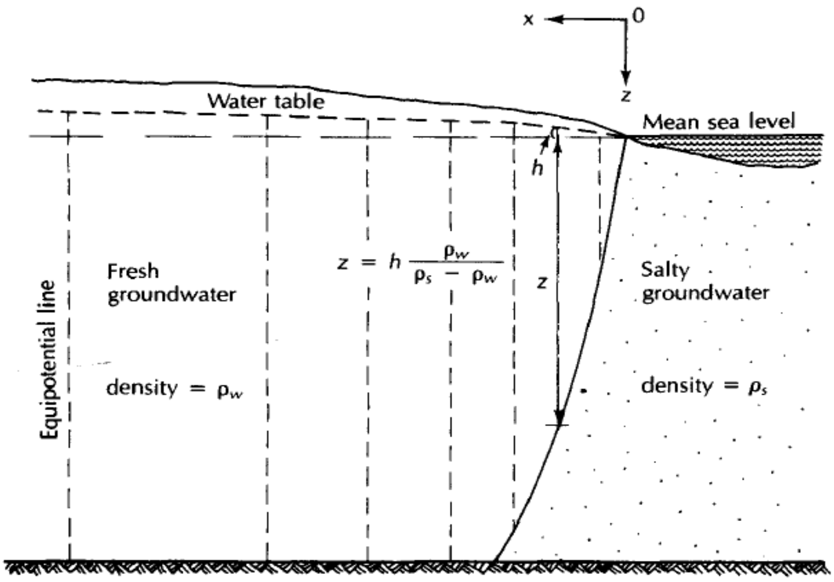


Figure 2.3. Relationship between freshwater head and depth of seawater interface (Fetter, 2001)

In reality, the interface is not sharp, and the seawater combines gradually with the freshwater by a zone of transition under the process of mechanical dispersion. The dispersion zone thickness depends on the physical characteristics of the aquifer and water particles movement due to tides or fluctuation due to recharge (Cooper, 1959). The transition zone depends on aquifer properties such as geological and hydrological and the extent of seawater intrusion. This transition or dispersion zone is a result of hydrodynamic dispersion of the dissolved matter and could be narrow or wide depending on the aquifer structure. Steady state reduces the transition zone thickness, whereas over pumping, low recharge, tides increase its thickness. The thickness of transition zones could variety from a few meters to kilometers in over-pumped aquifers (Todd, 1974).

2.4 Computer Codes to Simulate Seawater Intrusion

Through the years, a number of computer codes were developed to investigate seawater intrusion in coastal aquifers. These include numerical and analytical models. Finite difference and finite element methods are most widely used models. A number of software's have been used to model variable density flow and solute transport to investigate seawater intrusion in coastal aquifers. Some of the common codes used to simulate seawater intrusion are listed below.

2.4.1 SUTRA

SUTRA model, first released in 1984, is a two-dimensional groundwater model that simulates solute transport and is well-documented by (Voss, 1984). SUTRA is a finite-element simulation model for saturated- unsaturated, fluid-density-dependent groundwater flow with energy transport or chemically reactive single species solute transport. SUTRA may be employed for areal and cross-sectional modelling of saturated groundwater flow systems, and for cross-sectional modelling of unsaturated zone flow. Solute transport simulation using SUTRA may be employed to model natural or man-induced chemical species transport including processes of solute sorption, production and decay, and may be applied to analyze groundwater contaminant transport problems and aquifer restoration designs. This code has been widely used to simulate variable density flow in coastal areas. The 3D beta-version is available now.

2.4.2 MOC3D

MOC3D is a three-dimensional code to simulate density dependent groundwater flow and solute transport (Oude Essink, 1998). The model calculates variations in concentration of a single dissolved chemical content over time that are caused by advection transport, mechanical dispersion and diffusion, mixing (or dilution) from fluid sources, and mathematically simple chemical reactions (including linear sorption, which is represented by a retardation factor, and decay). The model can also simulate ground-water age transport and the effects of double porosity.

2.4.3 FEFLOW

FEFLOW is an acronym of Finite Element subsurface FLOW which is a 3D computer code, which employs the finite element method (Diersch, 1996). FEFLOW solves the governing flow, mass and heat transport equations in porous and fractured media by a multidimensional finite element method for complex geometric and parametric situations including variable fluid density, variable saturation, free surface(s), multispecies reaction kinetics, non-isothermal flow and multi diffusive effects.

2.4.4 SEAWAT

(Guo and Bennett, 1998) first documented the original SEAWAT concept of combining MODFLOW and MT3D into a single program solves the coupled flow and solute-transport equations and simulate three-dimensional variable density flow, transient groundwater flow.

SEAWAT uses either an explicit or implicit procedure to couple the ground-water flow equation with the solute-transport equation. The flow equation is resolved first for each time step with the explicit procedure. While the implicit procedure for coupling, the flow and transport equations are solved various times for the same time step until the maximum fluid density difference between consecutive iterations is less than a user-specified tolerance (Guo and Langevin, 2002).

3. MATERIAL AND METHOD

3.1 Description of Study Area

3.1.1 Location of Study Area

Bosaso is a coastal town located on the southern coast of the Gulf of Aden. Bosaso Plain is surrounded by mountains from the west, east and south and the Gulf of Aden from the north. The vegetation is more or less absent in the area and is covered by red soil and limestone boulders. Bosaso plain is a wide plain (approximately 70 km^2) having a triangular shape and extend for 22 km inland in the valley of Togga Balade toward Togga Biyo Kulule. The plain gently descending seaward of Gulf of Aden and mostly characterized by alluvial deposits. Bosaso is the third largest city in the country and its population is estimated at about 430,000 residents. The location of Bosaso Plain is shown in Figure 3.1. Bosaso is a commercial and major city of Puntland state. It has most of the industries and companies. The town is trading Centre and it links both northern and southern of the country. The city relies on groundwater as a source of freshwater.

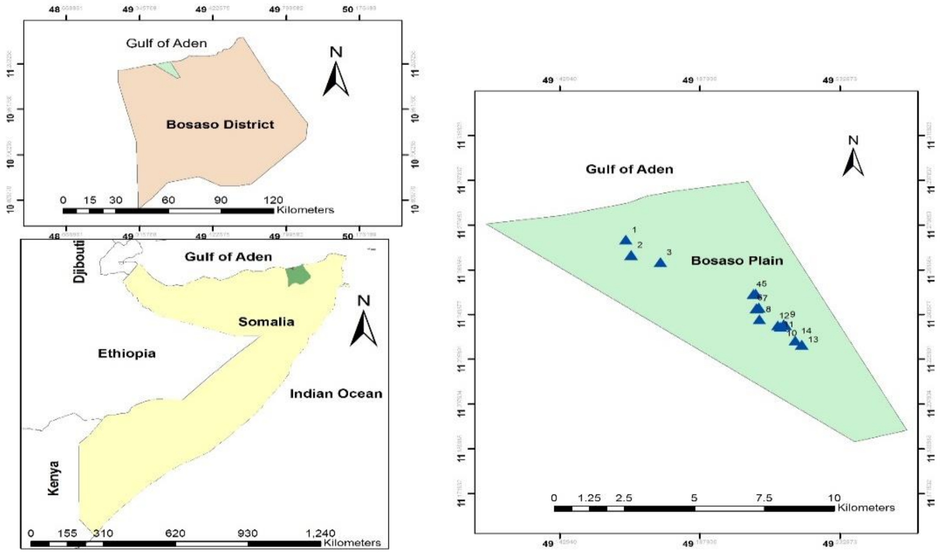


Figure 3.1. Geographical location of Bosaso Plain

3.1.2 Climate

The climate of the Bosaso city is a typical arid type with very high temperature in summer, which reach peaks of about 41 degrees centigrade in July and August and relative humidity of about 70%. During the winter however, the temperature drops and the climate become pleasant. As presented in Figure 3.2, the daily minimum temperatures range between 30°C to 20°C and the daily maximum temperature varies from 41°C to 30°C during the winter and summer respectively.

Bosaso is characterized by very scarce rainfall, generally less than 50mm/year as shown in Figure 3.3, a high evaporation rate, estimated at more than 300mm/year. Somalia in general has an arid to semi-arid climate; in general, evaporation is greater than precipitation.

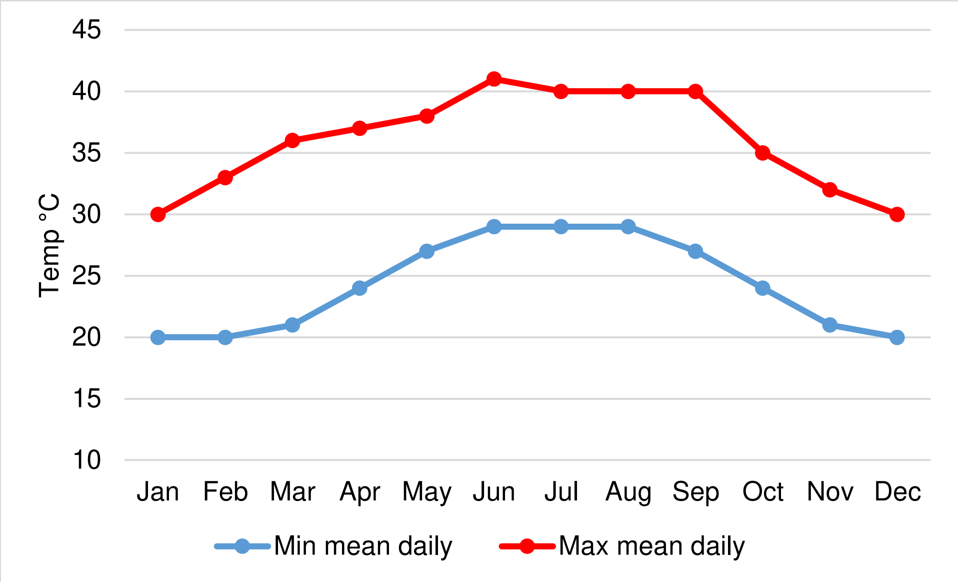


Figure 3.2. Daily average temperature in Bosaso

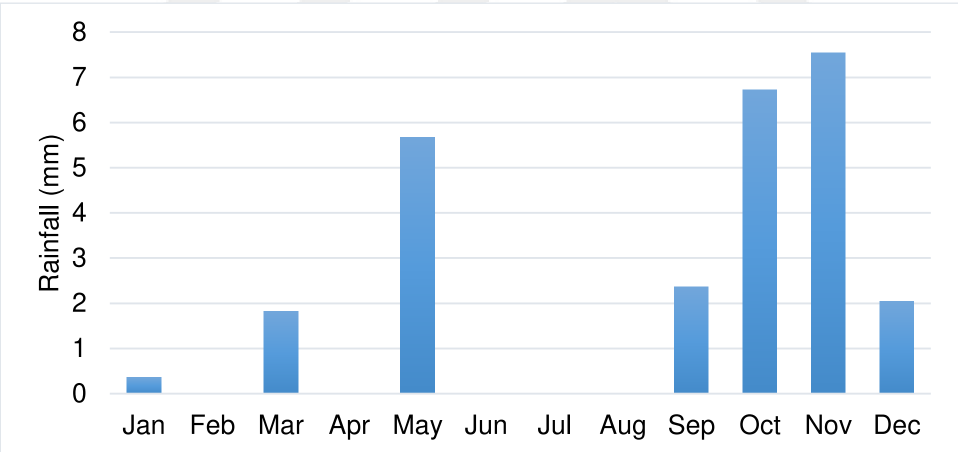


Figure 3.3. Temporal rainfall distribution for the Bosaso

3.1.3 Topography

The Bosaso Plain is surrounded by mountains from three sides (south, East and west) and in the north by the Gulf of Aden as shown in Figure 3.4. Surface elevation of the Bosaso Plain was derived from the digital elevation model. The surface elevation of the Bosaso Plain varies between 0 m mean sea level (msl) to 85 m above mean sea level (masl). Figure 3.5 shows the distribution of surface elevation of Bosaso Plain; the Two-dimensional view was drawn by using ArcGIS

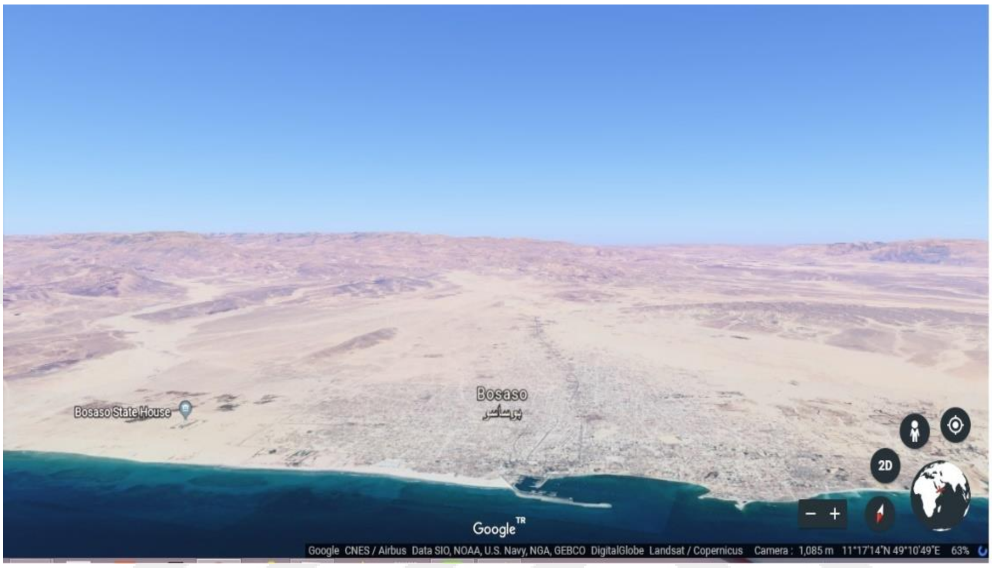


Figure 3.4. topography map of the Bosaso Plain

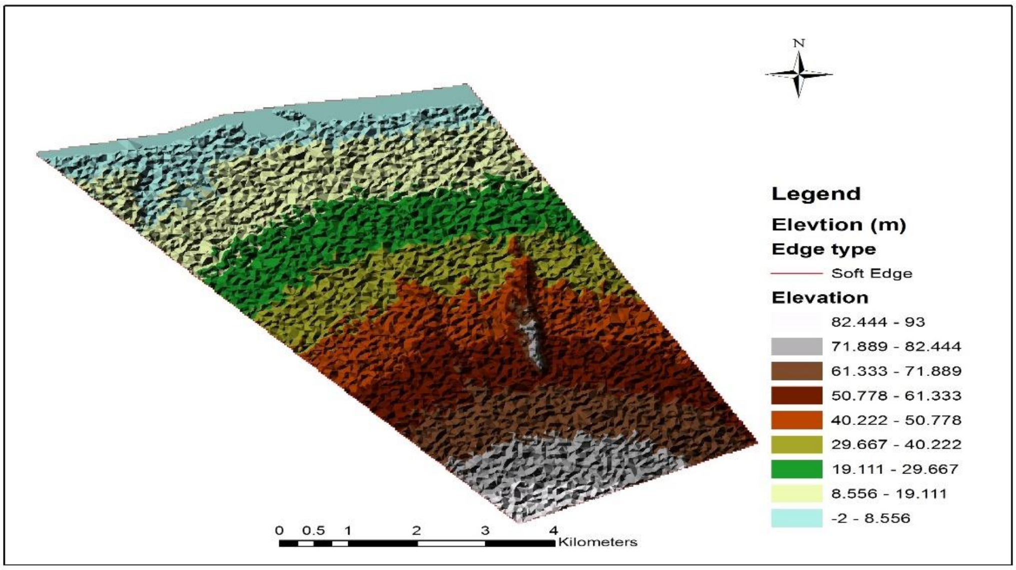


Figure 3.5. Surface elevation of the study area

3.2 Available Data

The available data of this study mainly consists of secondary and primary data. Secondary data were obtained from the Puntland State Agency for Water Energy and Natural Resources (PSAWEN) and were carried out 2013. The secondary data gives the geology, hydrogeology and hydrological of Bosaso aquifer and can be used as representative of the whole aquifer system. While the primary data were carried out in 2017 to study the hydro-chemical of the aquifer.

3.2.1 Hydrological Features

The hydrological features, for the most, reflect the pattern of the geo-tectonic structures. The hydrological surrounds of the study area can be divided into three main basins.

3.2.1.1 Dhag'an Basin

Dhag'an basin it is the widest as shown in Figure 3.6, with a surface of almost 1,600 km^2 which occupies most of the eastern section of the study area. The basin head lies southward of the escarpment edge with the top at an elevation of almost 1,800 above mean sea level (masl). The main course of the stream, in its middle section (between 300 and 200 masl of elevation), is characterized by running water even in the dry season. At the asphalt road cross, the average yield has been estimated about 180 l/s. below the elevation of 200 masl the water disappears in the ground. The valley descends NW ward up to hills belt which dams the basin 2.5 km before the coastline at Jaanka. In this site, the stream erosion opened a narrow of about 200 m in the hill range, in which the sea water penetrates. At the hills shoulder there is a shallow wells field with variable salinity water which becomes fresh when the flows reach the sea (Terre Solidali, 2013).

Figure 3.6. Bosaso Hydrological Basins (Terre Solidali, 2013)

3.2.1.2 Togga Balade Basin

Togga Balade basin the upper course of the stream runs between the Ahl Miskat Mountains, starting from an elevation of 1,770 masl. The whole basin extends on a surface of 950 km^2 as shown in Figure 3.6, of which almost 800 km^2 are at elevations above 500 masl. At the lower end of the upper section, there is the Gaa spring, which yield is estimated in the dry season about 80 l/s. The spring gives birth to a small water flow that disappears in the ground after 1-2 kilometers. The lower section of the basin is constituted by a narrow string, about 5 km wide and 35 km long, that ends in the slightly wider plain which surrounds the town of Bosaso. About 12 km from the sea have been noted phenomena of the capture of the Togga Balade course, by the western branch of T. Kulule. In other terms, part of the water of the T. Balade flows is recalled toward the T. Kulule branch. The phenomena could extend up to a complete capture of the course (Terre Solidali, 2013).

3.2.1.3 Togga Kulule

Togga Kulule is a small basin adjacent to the basin of T. Balade, eastward as shown in Figure 3.6. The basin is about 25 km long and has a small surface (about

200 km^2). Its head starts at 1,030 masl but it extends at elevations above 300 m only for 1/3rd of its length. About 6 km from the sea there is the thermal spring of Biyo Kulule (1-2 l/s) (Terre Solidali, 2013).

3.2.2 Geology and Hydrogeology

The Bosaso Plain is covered alluvial fanglomerates and alluvial deposits as shown in Figure 3.7. All the boreholes in the study area are located in alluvial deposits. The alluvial deposits consisting of calcrete soil, gravel and conglomerates underlain by cemented very hard limestone boulders. The very hard limestone boulders are followed by layers of clay light colored, Tertiary sediments comprising loose, unconsolidated alluvial sediments, sandy soils, erosional and depositional sandy clayey materials. The hydrogeological Section of the study area is shown in Figure 3.8. The main water supply in the city is located southeast of the city in the Biyo Kulule. There, 11 boreholes were drilled in alluvial sediments with an average depth of 60 m. The average pumping rate is around 10 l/s which enable a total groundwater extraction of ca. 100 l/s.

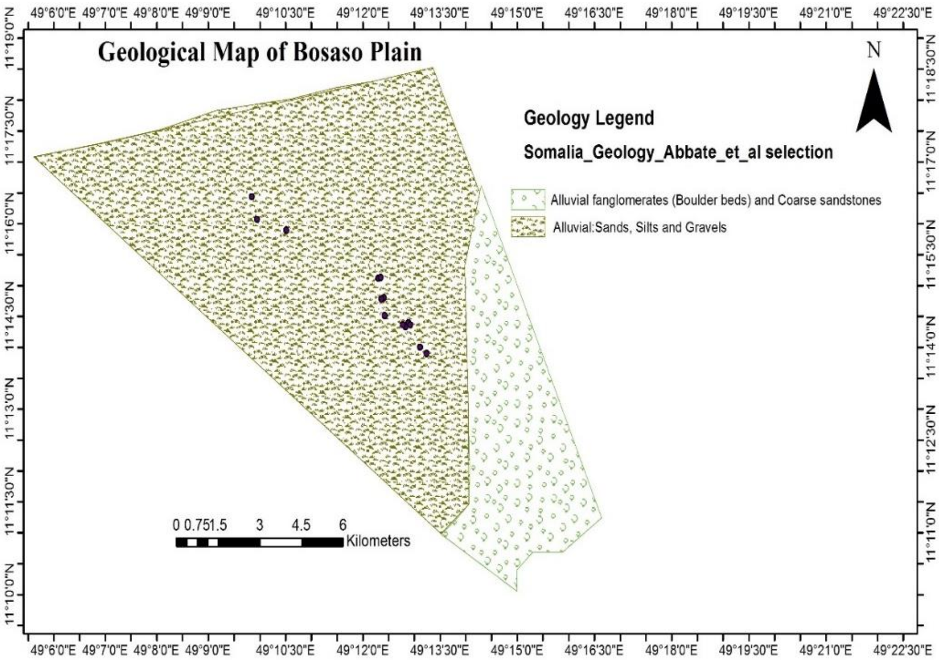


Figure 3.7. Geological map of the Bosaso Plain

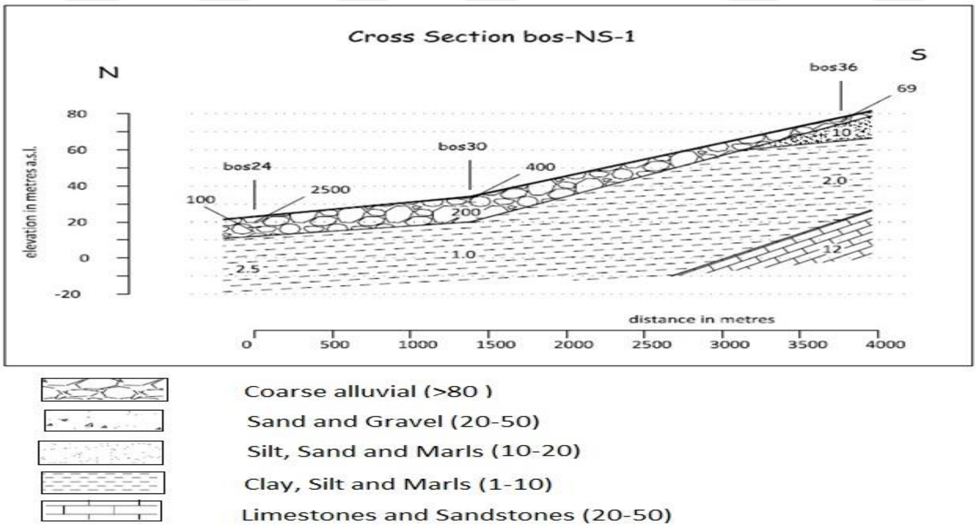


Figure 3.8. Hydrogeological cross section of the Bosaso Plain (Terre Solidali, 2013)

3.2.3 Aquifer Parameters

Pumping test was carried out in Bosaso Plain in 2013 to measure the aquifer parameters such as hydraulic conductivity (K), transmissivity (T) and specific yield (Sy). Five pumping tests have been carried out on five boreholes were selected to represent the entire aquifer system. The tests have been done with the pumps already installed in the boreholes. The test duration has been of 24 hours of continuous pumping, while the recovery endured for the time necessary for the water level to recover 80- 90 % of the draw-down. During the test have been measured the dynamic WL, the WEC and the temperature (Terre Solidali, 2013). This data will be used to define our conceptual model.

3.2.4 Groundwater Level and Salinity Monitoring

In the study area, there are 14 active public boreholes were static water level (SWL) and salinity measured. The depth of SWL decreases from far inland to coast. Table 3.1 shows Average groundwater levels and salinity for the period 2013.

Table 3.1. Average Static water level and salinity measured in 2013 (Terre Solidali, 2013)

No	Latitude	Longitude	Elevation	depth of borehole	Annual average SWL (m)	Annual average WEC (µS/cm)
B1	299593.7474	1246901.6735	8.3	23	-	10685
B2	299771.8288	1246217.9740	12.4	23	-	5050
B3	300805.0151	1245891.8081	20.6	28	-	4180
B4	304053.6147	1244447.9860	47.3	46	8.5	2111.6
B5	304129.1113	1244471.8623	46.3	52.5	5.3	2650
B6	304243.2905	1243856.0795	53.4	48.5	11.4	1777.2
B7	304158.9551	1243815.6627	53.3	57.4	11.7	1452
B8	304262.9885	1243326.0571	58.7	42	-	1570.4
B9	305112.3448	1243100.7388	62.6	63	24.2	1446
B10	304993.6784	1242981.9835	63.5	65	-	1399.4
B11	304902.3370	1243046.7021	62.7	78	-	1422.5
B12	305173.1496	1243042.8438	63	63.8	24.4	1452.2
B13	305741.3141	1242187.5792	71.1	69.5	28.4	4196.667
B14	305509.7963	1242369.3013	71	72		1738.5

According to (Walton, 1989), the relationship between TDS (mg/ l) and EC (µS/cm) can be expressed as;

$$\text{TDS} = 0.67 \times \text{EC} \tag{3.1}$$

3.2.5 Water Quality

Water quality was carried out to study hydro-chemical of the groundwater. Groundwater sampling locations have been distributed spatially to cover the entire study area. In July 2018, groundwater samples were collected from shallow groundwater wells and deep boreholes in the study area. A total of 22 groundwater wells was visited, and water samples were collected in polythene bottles at each sampling location. Location of sampling sites was determined by utilizing a handheld Garmin GPS device. The collected samples were returned to the water quality laboratory of Department of Agricultural Structures and Irrigation in Cukurova University within four days. Groundwater quality parameter such as pH, electrical conductivity (EC, dS/m), total dissolved solids (TDS, mg/ l), sodium (Na, mg/ l), chloride (Cl, mg/ l), calcium (Ca, mg/ l) and Magnesium (Mg, mg/ l) Carbonate (CO3 mg/l), Bicarbonate (HCO3 mg/l), Sulfate (SO4 mg/l), potassium (K mg/l). Based on (Ayers and Westcot, 1994), TDS was calculated by using chemical analysis results of Na, K, Ca, Mg, Cl, CO3, HCO3, SO4 ions in the unit of mg/l. Additionally, following the procedures given in (Fetter et al., 2017), sodium adsorption ratio (SAR) was calculated for each water sampling location by using Na, Ca and Mg analysis results in me l^{-1} unit.

3.3 Modelling Seawater Intrusion by Using SEAWAT

To simulate seawater intrusion for this study, SEAWAT code was selected. A major advantage in using SEAWAT is based on the variable density flow approach and it can read and writes standard data sets for both MODFLOW and MT3DMS. SEAWAT code was tested by simulating five benchmark problems involving variable-density groundwater flow, including the Elder problem (Guo and Langevin, 2002)

3.3.1 Preparation of MODFLOW Input Packages for SEAWAT

The MODFLOW input packages for SEAWAT are:

- Basic (BAS) package which used to specify initial and boundary condition such as (active cells, inactive cells and constant head cells)
- Output Control (OC) option which is used to control output results to saved or printed as user specified.

- Block-Centered Flow (BCF) package is used to input distributed spatial parameters such as aquifer top elevations, aquifer bottom elevations, hydraulic conductivity and storage coefficients
- Well (WEL) package used to simulates the recharge and discharge of water from wells.
- Drain (DRN) package used to removes water from the aquifers and to simulate small springs.
- River (RIV) package is used to simulate the effects of flow between surface and subsurface water.
- Evapotranspiration (EVT) package is used simulate the effects of plant transpiration and direct evapotranspiration in removing water from the saturated groundwater regime.
- General-Head Boundary (GHB) package is used Simulate head-dependent recharge or discharge across an aquifer boundary
- Recharge (RCH) package is used to simulate areal distributed recharge to the subsurface system
- Time-Varying Constant Head (CHD) package is used to simulate time varying head.
- Users can select one of the three solver packages, including Strongly Implicit Procedure (SIP), Successive Over-Relaxation (SOR), and Preconditioned Conjugate Gradient (PCG)

4. RESULTS AND DISCUSSION

4.1 Groundwater Quality Analysis

The over pumping of groundwater in the Bosaso aquifer in recent decades has caused to a worsening in the quality of water in most aquifers**.** The laboratory result of water quality collected from Bosaso city are given Table 4.1. The interpretation of laboratory analysis results using (WHO, 2008) standards revealed that the most of groundwater in the Bosaso Plain is unsafe for drinking purposes due to salinization, except in the central area (Biyo Kulule) which are safe for drinking.

4.1.1 pH

Basically, pH is the measure of hydrogen ion concentration in the water. PH in the study area range of 7.031 to 8.00 as can be seen in Table 4.1. Which clearly reveled the pH in study area is lies within the pH limit for drinking water specified as 6.5 -8.5 (WHO, 2008). It can be concluded that groundwater in Bosaso Plain is safe for drinking in terms with pH.

4.1.2 Electrical Conductivity (EC)

Electrical conductivity (EC) is a measure of water potential to deliver an electric current. The higher the salinity concentrations of water are, the more EC is measured. Pursuant thereto, EC values of groundwater samples was found to be higher than 1.5 dS/m except three samples, and groundwater are classified as saline water according to (Langenegger, 1990). Spatial distribution map of EC (Figure 4.1a) shows that EC is increasing from South-east inland to the North coastline of the study area. As seen in Figure 4b, EC of groundwater is remarkably increasing while approaching the shoreline. Substantial rises in EC values shoreward may be a clear indication of seawater intrusion into coastal aquifers of the Bosaso Plain.

4.1.3 Total Dissolved Solids (TDS)

Total dissolved solids (TDS) contain inorganic salts such as (potassium, magnesium, calcium, sodium, bicarbonates, sulfates and chlorides) and some small quantities of organic matter. The values of TDS in groundwater in study area vary from 1035.31 mg/l to 10,083.5 mg/l, revealing the very high and dominant salinization problems in some specific locations in the study area. TDS map in Figure 4.1b shows trend increasing while approaching the sea and that is the evidence of seawater is influence into Bosaso aquifer

4.1.4 Chloride

The source of chloride in groundwater is both natural and anthropogenic, such as run-off containing road deicing salts, the use of inorganic fertilizers, landfill leachates, septic tank effluents, animal feeds, industrial effluents, and irrigation drainage and seawater intrusion in coastal areas (Karanth, 1987). The chloride ion in fresh water normally is lower concentration typically less than 100 mg/l, except brackish or saline water (Fetter et al., 2017). Chloride concentrations of groundwater samples varied from 149.74 to 4502.4 mg/l. The highest concentration of chloride is witnessed to be in North along the coastline. As shown Figure 4.1c the closer to the sea is, the higher Cl concentration is in the groundwater. The increasing trend in Cl concentration towards the sea may be an apparent indication of seawater intrusion to the coastal aquifer in use. Likewise, spatial distribution of Na concentration supported the postulate of sea water intrusion in the study site.

4.1.5 Sodium

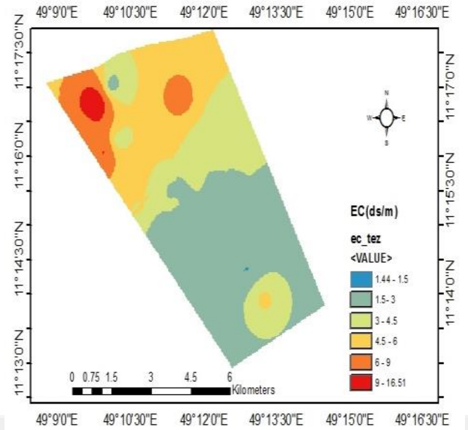
All groundwater samples contain sodium element to some extent because most rocks and soils naturally contain sodium compounds.). In our study, the aquifer is contiguous to the sea, and the area is almost flat with the slope of less than 0.6%, on the average. Sodium concentration map in Figure 4.1d shows an increasing trend in the concentrations from southeast to north. It is important to emphasize that the variability in sodium concentrations are extremely high (CV>130%), revealing the evidence of seawater.

4.1.6 Calcium

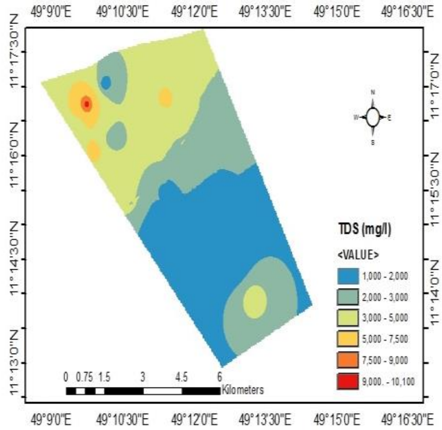
Source calcium and magnesium in groundwater is from dissolved certain rocks and minerals such as limestone and gypsum. Calcium concentration in the study area vary from 96.8- 708.5 mg/ las can be seen in Table 4.1. Most of the groundwater samples exceed 100 mg/l which is the acceptable level limit by WHO. But in the southeast area is less than the maximum permissible limit by WHO 200 mg/l.

4.1.7 Magnesium

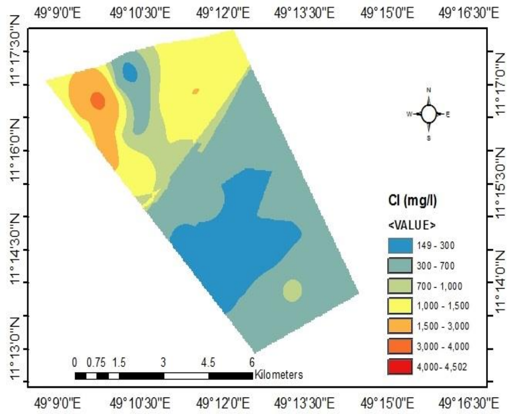
The Magnesium concentration in the Bosaso Plain ranges between 67.5 to 487.1 mg/ l as shown in Table 4.1. All groundwater samples in the northwest of the study area had Mg concentration above (150 mg/l) which is the maximum permissible limit stated by WHO. This indicated that the water is not safe for drinking purposes for the northwest. But for southeast is below the threshold value and can be safe for drinking.



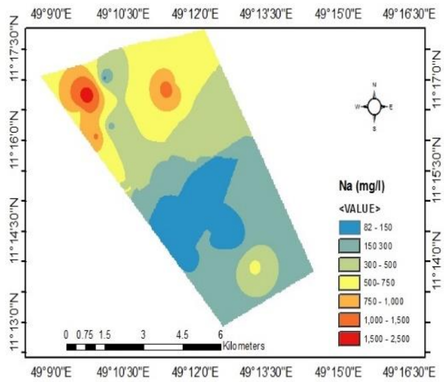
(a)



(b)



(c)



(d)

Figure 4.1. Spatial distribution map of groundwater parameters in Bosaso plain: (a) EC, (b) TDS (c) CI (d) Na

4.1.8 Linear Regression Modelling

Results of the linear regression show that the relationships between the examined parameters has a very strong relationship as shown in Figure 4.2 – 4.4. The determination coefficient was found between CI and the EC (r^2= 0.98) whereas the observed correlation between Na and EC (r^2 =0.95) and Na and CI (r^2 =0.93).

This strong relationships between above parameters indicates a strong influence of seawater intrusion into the Bosaso plain.

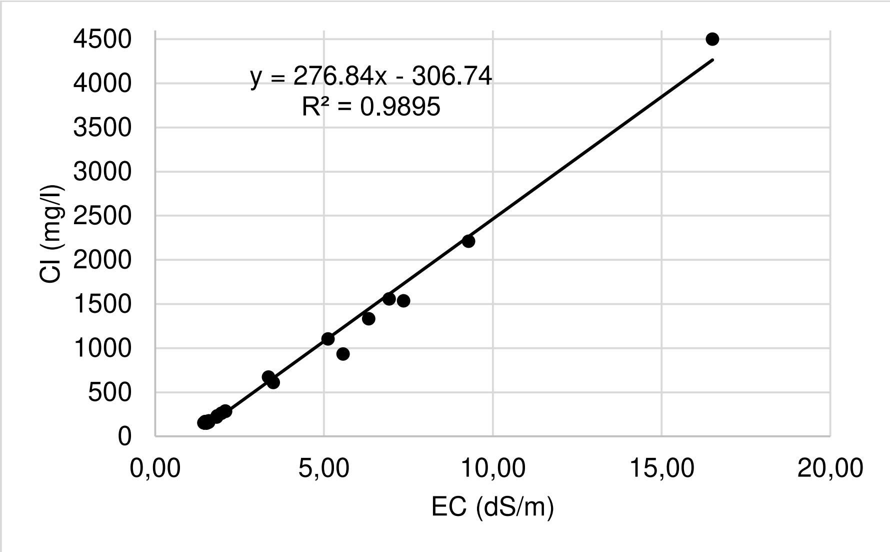


Figure 4.2. The correlation between the Chloride (Cl) and the Electrical Conductivity (EC) in Bosaso plain

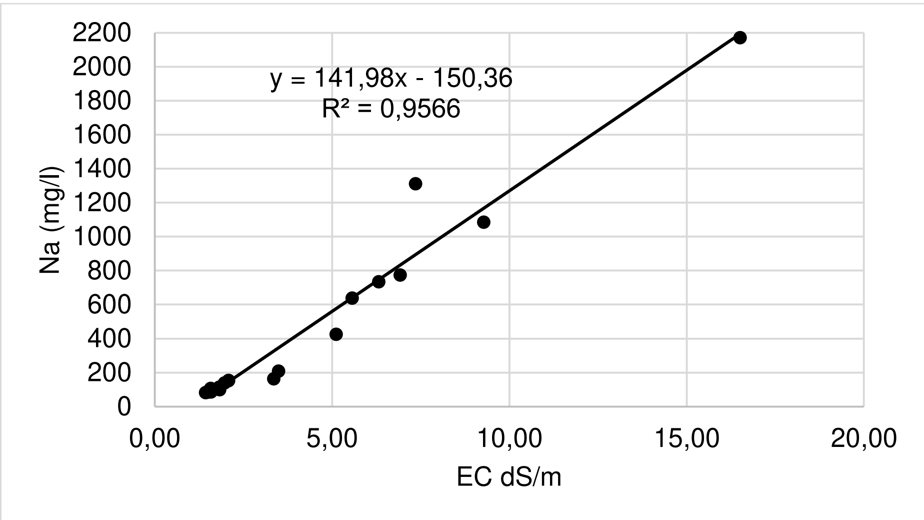


Figure 4.3. The correlation between the Sodium (Na) and the Electrical Conductivity (EC)Figure 4. 1.

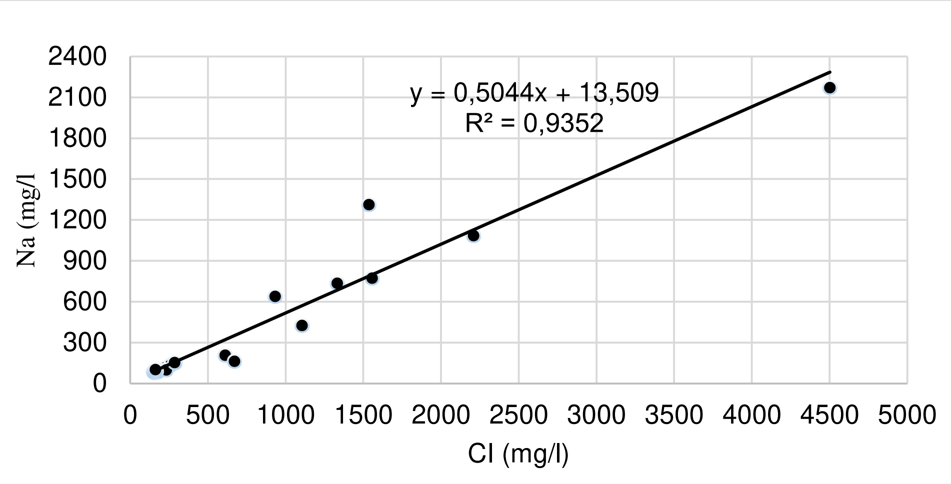


Figure 4.4. The correlation between the Sodium (Na)) and the Chloride (Cl)

Table 4.1. Hydrochemical analysis of groundwater in the Bosaso Plain

ID	EC (dS/m)	TDS (mg/l)	PH	Ca (mg/l)	Mg (mg/l)	C03 (mg/l)	HCO3 (mg/l)	Cl (mg/l)	K (mg/l)	Na (mg/l)	SO4 (mg/l)	SAR	Water type
B1	1.60	1175.83	7.83	147.93	82.30	29.42	289.14	177.27	7.44	86.93	355.40	1.42	Ca-Mg-Na-SO4-Cl-HCO3
B2	16.51	10083.50	7.20	708.48	487.06	29.42	235.96	4502.39	53.56	2172.14	1894.48	15.39	Na-Mg-Ca-Cl-SO4
B3	6.32	4105.15	7.50	335.89	219.25	29.42	232.64	1332.13	21.33	735.46	1199.04	7.67	Na-Mg-Ca-Cl-SO4
B4	3.50	2064.52	7.29	239.13	151.79	29.42	305.75	610.99	12.43	208.02	506.99	2.59	Mg-Ca-Na-Cl-SO4
B5	1.82	1327.49	7.30	132.35	106.59	19.61	335.66	220.30	7.44	114.05	391.47	1.79	Mg-Ca-Na-SO4-Cl-HCO3
B6	1.59	1121.09	8.00	96.76	94.44	29.42	289.14	177.27	6.10	106.96	320.99	1.85	Mg-Ca-Na-SO4-Cl-HCO3
B7	3.36	2006.48	7.72	228.01	174.72	9.81	398.81	671.23	10.16	163.03	350.71	1.98	Mg-Ca-Na-Cl-SO4
B8	2.08	1452.03	7.86	161.27	93.77	29.42	309.08	287.42	10.16	152.59	408.31	2.37	Ca-Mg-Na-SO4-Cl-HCO3
B9	1.97	1402.48	7.27	146.81	99.84	29.42	355.60	261.61	7.44	138.52	363.24	2.16	Mg-Ca-Na-SO4-Cl-HCO3
B10	1.44	1035.31	7.31	110.11	81.63	29.42	302.43	154.90	5.22	82.22	269.39	1.45	Mg-Ca-Na-SO4-HCO3-Cl
B11	1.52	1123.40	7.44	125.68	85.00	29.42	312.40	149.74	5.22	86.93	329.01	1.47	Mg-Ca-Na-SO4-HCO3-Cl
B12	1.84	1309.44	7.34	156.82	97.82	29.42	329.02	232.35	6.10	100.08	357.83	1.55	Mg-Ca-Na-SO4-Cl-HCO3
B13	1.48	1041.65	7.32	122.34	78.25	39.23	235.96	166.95	5.66	83.77	309.49	1.46	Mg-Ca-Na-SO4-Cl-HCO3
B14	5.57	4439.11	7.22	334.78	320.44	19.61	225.99	932.83	16.91	638.59	1949.95	5.99	Na-Mg-Ca-SO4-Cl
B15	1.50	1086.93	7.25	126.79	67.46	0.00	451.98	168.67	5.66	88.53	177.84	1.58	Ca-Mg-Na-HCO3-Cl-SO4
B16	1.56	1132.54	7.25	149.04	68.81	29.42	322.37	158.34	5.66	90.14	308.76	1.53	Ca-Mg-Na-SO4-HCO3-Cl
B17	1.58	1132.04	7.50	141.25	67.46	29.42	312.40	161.78	5.66	101.78	312.28	1.76	Ca-Mg-Na-SO4-HCO3-Cl
B18	2.09	1471.39	7.44	154.60	101.19	29.42	338.99	285.70	6.54	154.66	400.29	2.38	Mg-Ca-Na-SO4-Cl-HCO3
B19	5.12	3377.13	7.46	306.97	270.52	29.42	279.17	1104.94	13.78	425.62	946.71	4.27	Mg-Na-Ca-Cl-SO4
B20	9.28	6130.27	7.03	431.54	407.46	39.23	216.02	2209.89	24.03	1086.07	1716.04	9.01	Na-Mg-Ca-Cl-SO4
B21	6.93	4437.75	7.59	279.17	316.39	39.23	272.52	1557.59	21.78	774.52	1176.55	7.54	Na-Mg-Cl-SO4
B22	7.36	6183.36	7.10	300.30	310.99	39.23	362.25	1536.94	27.33	1312.46	2293.87	12.68	Na-Mg-SO4-Cl

4.1.9 Hydrochemical Facies

The hydrochemical facies in the study area can be easily obtained by plotting Piper diagram (Piper, 1944). The diagram is used to visualize and understand the geochemical common ions in groundwater, where concentration is assigned in % meq/l. Figure 4.5 shows the major cation and anion in the Bosaso Plain. The piper diagram shows that the dominant water type in study area Na-Mg-SO4-Cl and Mg-Ca-Na-SO4-Cl-HCO3. An examination of Figure 4.5 - 4.6 demonstrates the water type in the study area can be classified as mixing to saline water type. Therefore, Bosaso aquifer is affected seawater intrusion and its source from the north of the aquifer (Gulf of Aden).

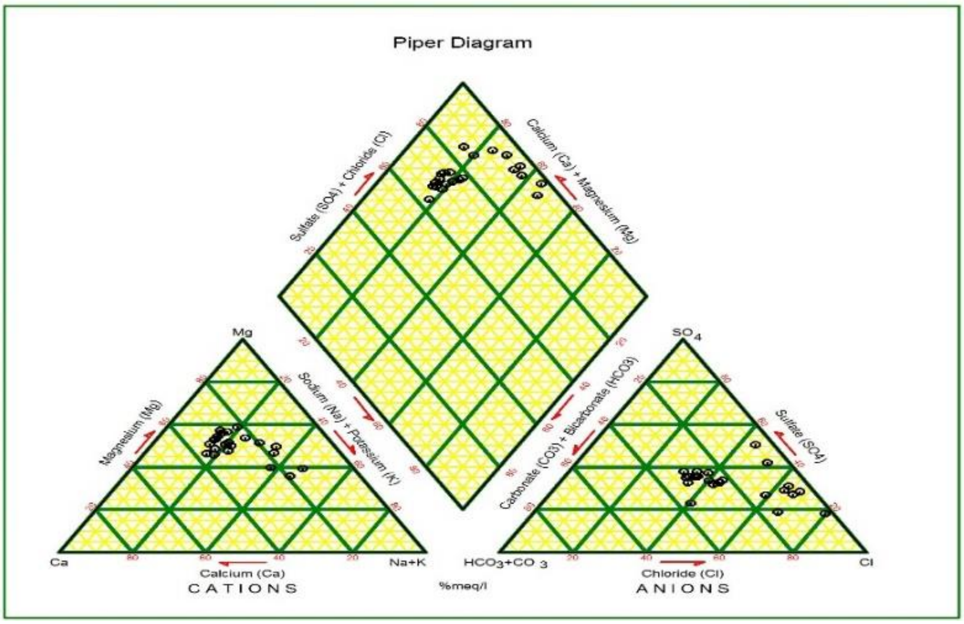


Figure 4.5. Piper diagram for the groundwater of Bosaso plain

(Appelo and Postma, 1993)

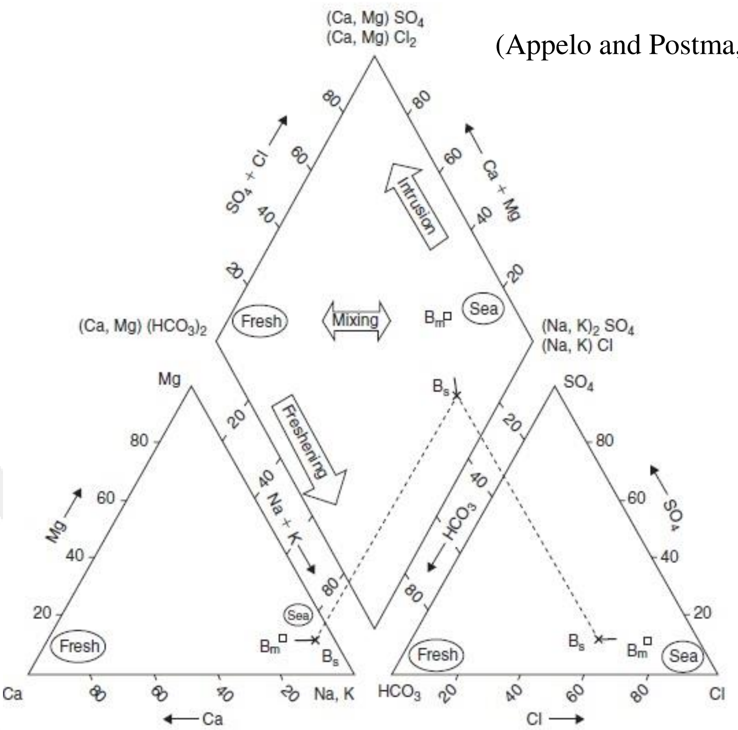


Figure 4.6. Piper plot showing average compositions of fresh water and seawater

4.2 Groundwater Flow Model Development

In this study, we utilized Visual MODFLOW Flex 5.1 which is graphical user interface for MODFLOW to model groundwater flow and simulate the seawater intrusion. Flow chart showing the groundwater modelling procedure of the Bosaso Plain is given in Figure 4.7.

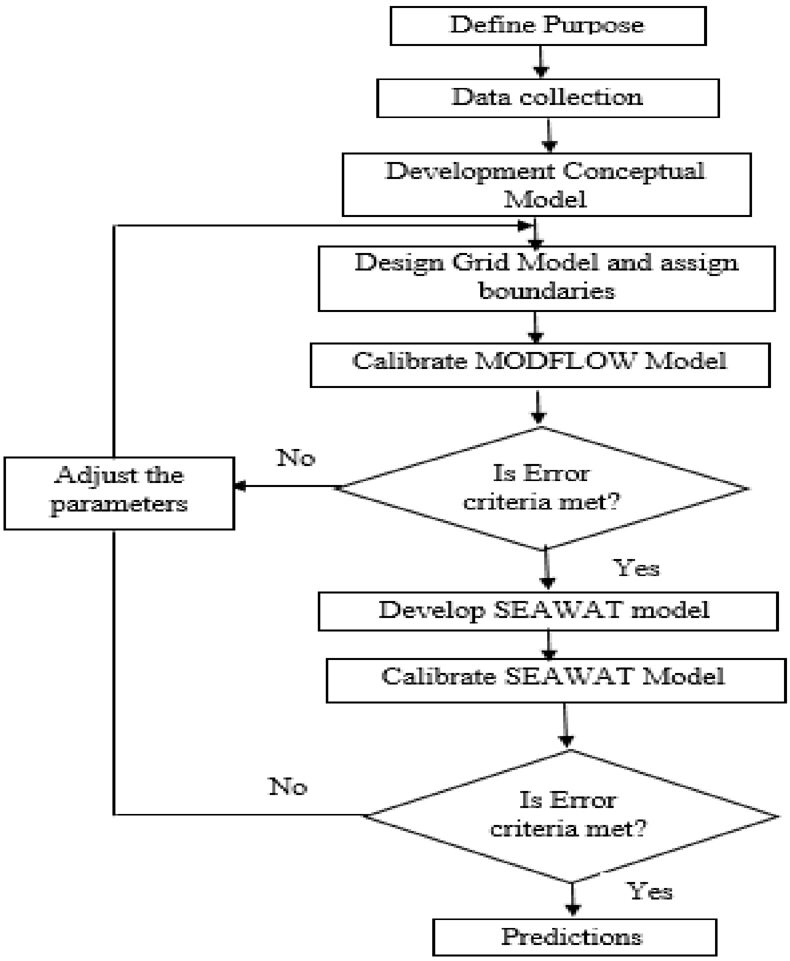


Figure 4.7. Flowchart of groundwater modelling procedure

4.3 Model Conceptualization

Conceptualization groundwater flow model is a process in which data describing subsurface hydrogeology are systematically gathered to define groundwater flow and solute transport processes at the study area. The closer the conceptual view to the field conditions, the more accurate the result of groundwater modelling.

4.3.1 Base Map

The base map was used to gain insight into the model dimensions. In addition, it can be used to locate the important features of the model, such as wells and observation targets. The Visual MODFLOW (VMOD) uses the Universal Transverse Mercator (UTM) coordinates system. Therefore, using ArcGIS10.1 geographical coordinate of base map and observation wells were converted to UTM (WGS 1984 UTM zone 39N). Afterwards, the base map was imported into VMOD model. The base map in MODFLOW functions as a boundary, hence contains no specific data used in the numerical calculations and has no effect on the simulation results. Figure 4.8 shows the 3D base map for the study area.

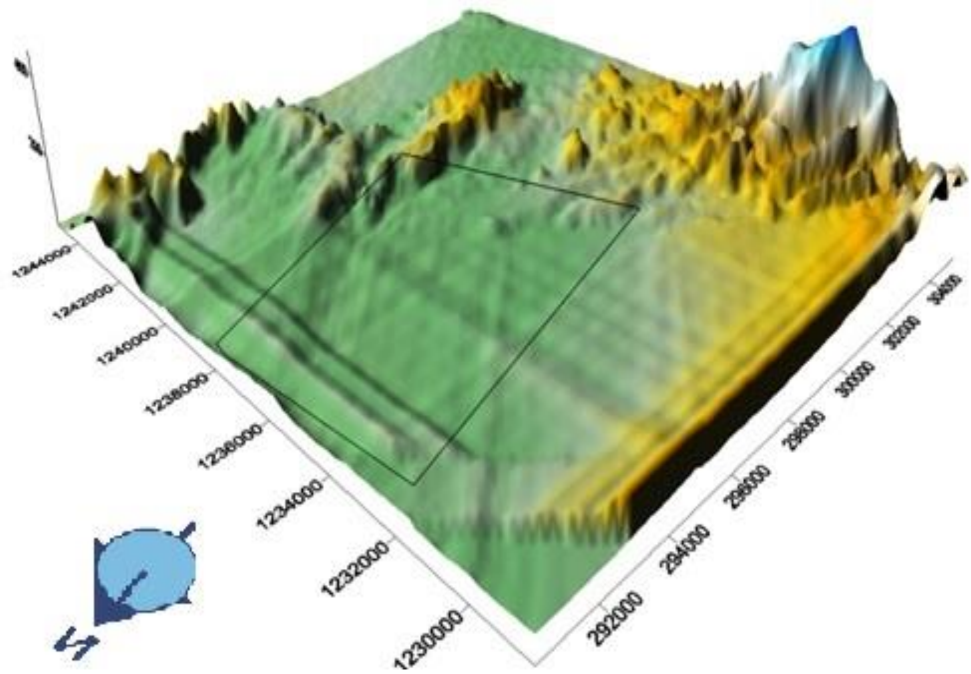


Figure 4.8. 3D base map FOR Bosaso plain (the polygon is the boundary of the study area)

4.3.2 Model Design

A finite difference grid consisting 1 layer, 92 rows and 107 columns was generated in the Bosaso Plain as can be seen in the Figure 4.9. Hence, the model had a total of 9844 cells with 4825 active cells and 5019 inactive cells.in addition, each cell is containing 100 m x 100 m in the horizontal plane. The interesting model area covers 48.25 km^2. Since the bottom layer of the aquifer is impermeable one-layer model containing of alluvial material (sand and gravel) was considered. The eastern and western boundary along were assumed to be no flow boundary condition (Neumann boundary).

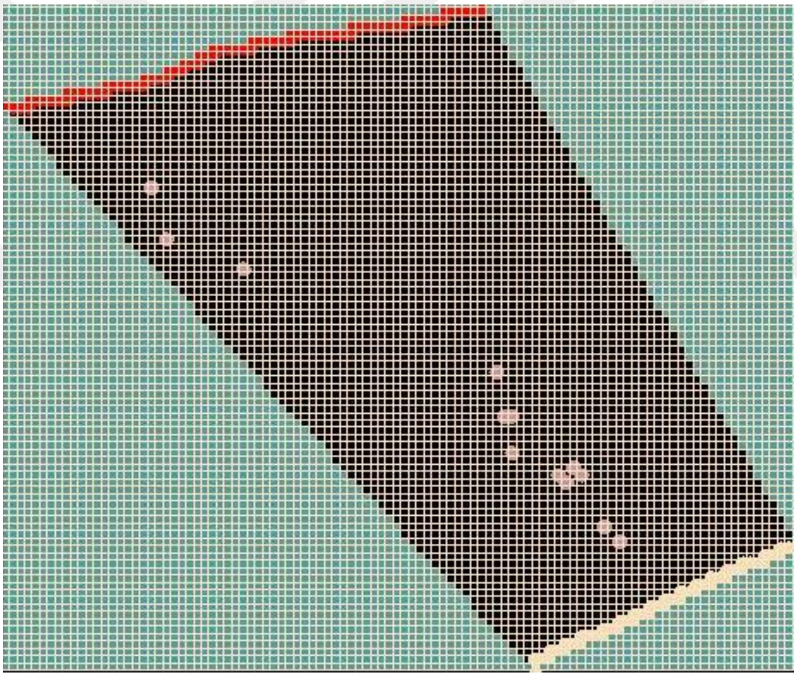


Figure 4.9. Finite difference grid for Bosaso plain

4.3.3 Layer Elevation

The Digital Elevation Model (DEM) for the top surface of the model was obtained directly from SRTM data (NASA Shuttle Radar Topography Mission) with 30 m-resolution. Afterwards, using the ArcGIS conversion tools the DEM was converted into point file. Then, the point files were assigned to the VMOD as top elevation of the model. The bottom elevation of the aquifer was assigned by interpolating the depth of wells the 2-dimentional horizons are shown (Figure 4.10). After horizons was created the aquifer structural zone were generated and later the hydrogeological parameters will be assigned (Figure 4.11).

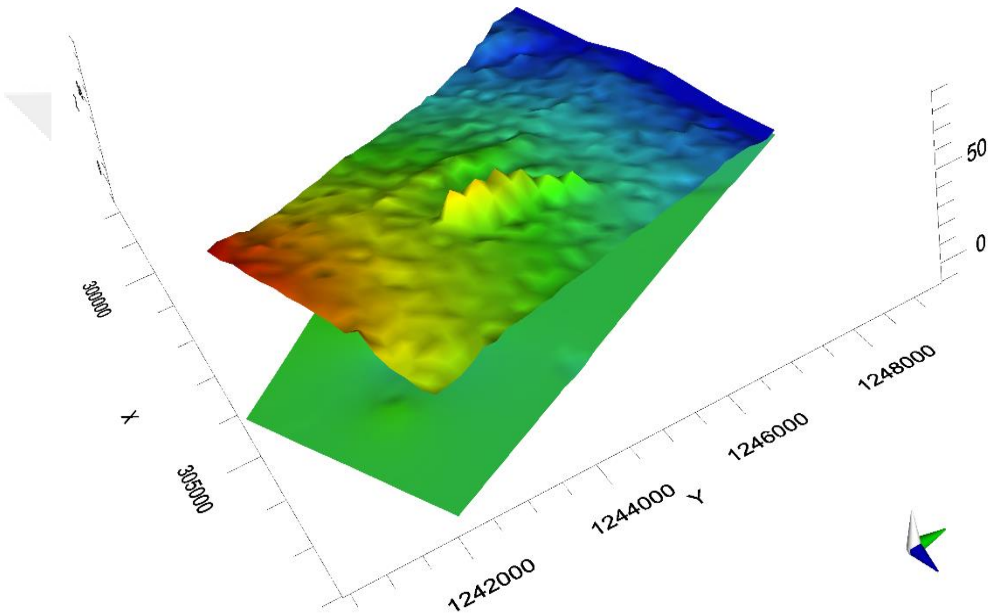


Figure 4.10. Bosaso Aquifer surface and base elevation

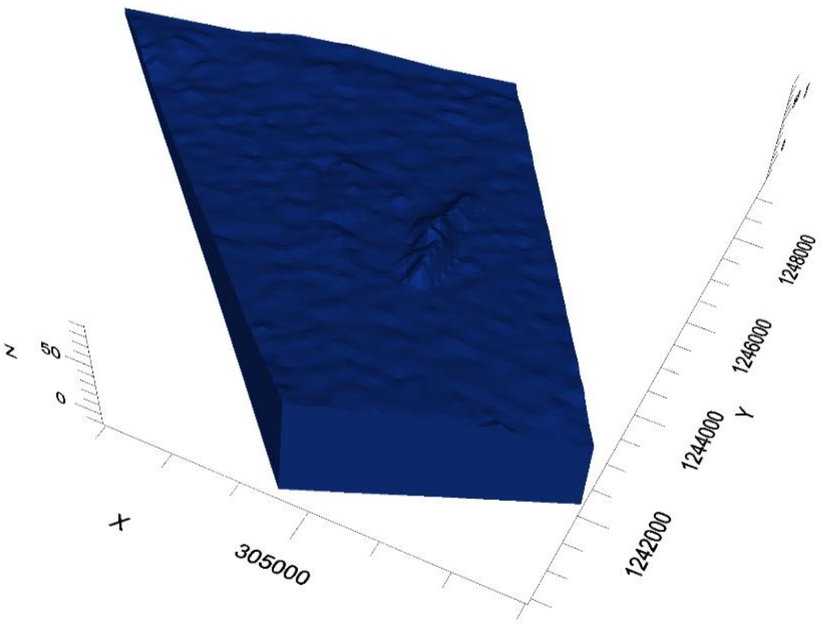


Figure 4.11. 3D view of Bosaso aquifer structure

4.3.4 4 Hydraulic Conductivity

Hydraulic conductivity is one of the key model parameters. It measures the permeability of the aquifer. Using data in Table 1 hydraulic conductivity were assigned into the model by diving model into 4 zones (Figure 4.12). Then, each zone was assigned its specific value in a unit of meter per a day. In addition, the hydraulic conductivity in longitudinal direction k_x, lateral direction k_y were assumed to same value since the formation of the layer is sand and vertical direction k_z, was taken $0.1k_x$. The initial hydraulic conductivity in the Bosaso Plain varies between 12 to 1470 m/day.

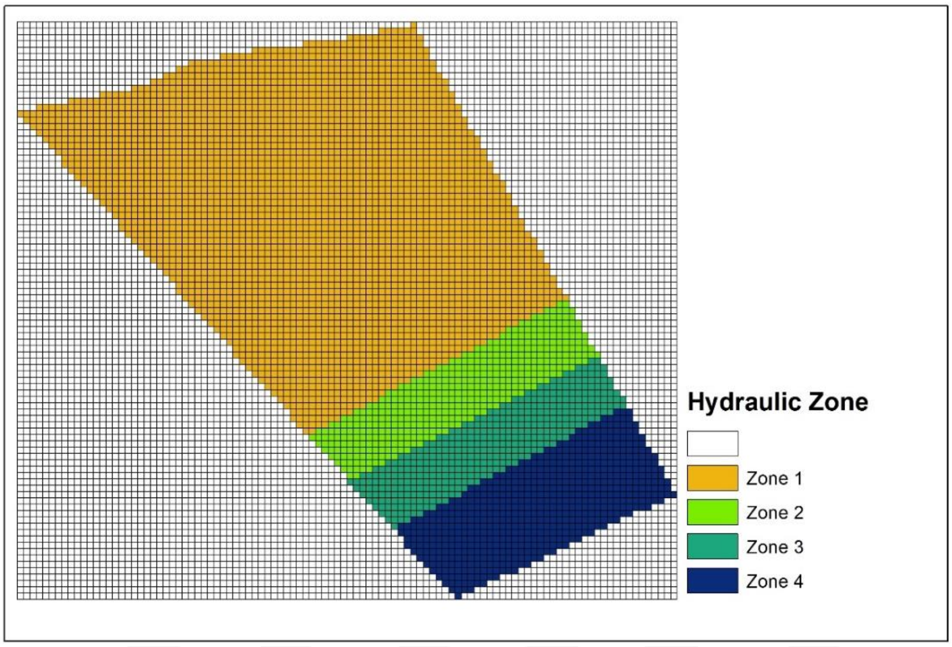


Figure 4.12. Hydraulic conductivity zones in Bosaso plain

4.3.5 Constant Head

A head and/or concentration that does not vary throughout the simulation i s assigned as a constant head boundary condition. For this model, all nodes along the northern side representing the coastline of the Gulf of Aden (6.5 km) was assigned to a constant head (Dirichlet boundary) condition with 0.0 m elevation and constant concentration of 35000 mg/l (Figure 4.9).

4.3.6 Recharge

Since the climate of the Bosaso Plain is the arid type, it's characterized by very scarce rainfall, and receives 30 mm/year with high evaporation rate of 300mm/year which results in no direct recharge. In addition, the Bosaso plain aquifer is recharge by Mountain front recharge (MFR) which is the contribution rainfall on surrounding mountains. Based on the study carried out (TS, 2012) they calculated annually recharge of Bosaso plain by considering all three hydrological basins that contributed (Figure 3.6). The study estimated a volume of 150 million m^3/year of runoff probably enters in the plain. The runoff rarely reaches the sea and for this reason a prudential estimate of 30 million of m^3/year (85000 m^3/day) is available as recharge. Therefore, MFR 85000 m^3/day was assigned along the mountain front in the south of the plain, by applies specified flux stresses to the aquifer system as seen in Figure 4.9.

4.3.7 Groundwater Abstraction

The groundwater is a major freshwater source of in the Bosaso city. Water demand in Bosaso is increasing due to rapid population growth. In the Bosaso, the groundwater is used for of drinking, industrial and irrigation water. The volume extracted by public governed by Golden Utilities Management Company (GUMCO), have a pump rate of 3000 m^3/day while Private boreholes have discharge approximately 5000 m^3/day, respectively (Terre Solidali, 2013). The total discharge rate of 8000 m^3/day was distributed equally to all 14 production wells in the model. Hence, it assigned as WELL with a negative sign to simulate as discharge well.

4.4 Calibration of the MODFLOW

Model calibration is the process to adjust the model's input parameters in order to match the reality of field conditions to attain the best representation of the aquifer system under certain acceptable criteria. The model calibration involved a trial and error adjustment procedure of the model inputs data, observed heads were compared to simulated heads in steady state condition. (Anderson et al., 2015).

The calibration of steady state simulation was carried by using automated parameter estimation code (PEST). The average static water level measured in 2013 were taken as the target of steady state calibration as shown (Table 2). Hydraulic conductivity values estimated by pumping test results was used as the initial values for steady state calibration. The hydraulic conductivity values were adjusted by sequential trial and error runs for all the zones until the reasonable match between the observed and simulated heads was obtained. The calibration of a model is mathematically measured and evaluated by using error statistics such as Mean Error (ME), Mean Absolute Error (MAE) and root mean square (RMS) which are defined by following equations:

$$\mathrm{ME} = \frac{\sum_{i=1}^{n}(S_i - O_i)}{n} \quad (4.1)$$

$$\mathrm{ARM} = \frac{\sum_{i=1}^{n}|S_i - O_i|}{n} \quad (4.2)$$

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} \quad (4.3)$$

Where:
S_i: Model simulated head at observation point *i*
O_i: Measured head at observation location *i*
n: Number points for observation

The root mean square (RMS) and the determination coefficient (r^2) error between observed and simulated heads, were used to evaluate how the observed heads compared to the model simulated heads. To date there is no established standard to evaluate the calibration process. A common thumb rule is that the RMS should be less than 10% for well calibrated model (Anderson et al., 2015). Statistical measures have been evaluated between observed and simulated heads as shown in Table 4.2. In addition, the model calibration can be accepted as good match when r^2 is greater than 0.6. After the completion of steady state calibration with the RMS of 7.6 % m and r^2 of 0.97 m are achieved, which shows a good match between the observed and calculated heads. Table 4.2 shows the residual error between observed and calculated heads. The Figure 4.13 shows the steady state calibration matching between observed and calculated heads. Calibrated model hydraulic conductivity is presented in Table 4.3. Contour map in Figure 4.14 shows that groundwater generally flows from south to north across the Bosaso Plain.

Table 4.2. Residual error between observed and calculated heads

Target well	Observed head (m)	Simulated head (m)	Residual head (m)
B1	8.5	9.7	1.2
B2	5.3	9.7	4.4
B3	11.4	12.2	0.8
B4	11.7	11.4	-0.3
B5	24.2	24.0	-0.2
B6	24.4	24.2	-0.2
B7	28.4	28.1	-0.3
Min. Residual			-0.16
Max. Residual			4.39
Residual mean			0.77
Abs. Residual mean			1.052
Standard error of the estimate			1.75
Normalized RMS			7.6 %

Table 4.3. Calibrated hydraulic conductive values

Zone	Initial value (m/day)	Calibrated value (m/day)
1	1468	1000
2	40	107
3	24	393
4	12	74

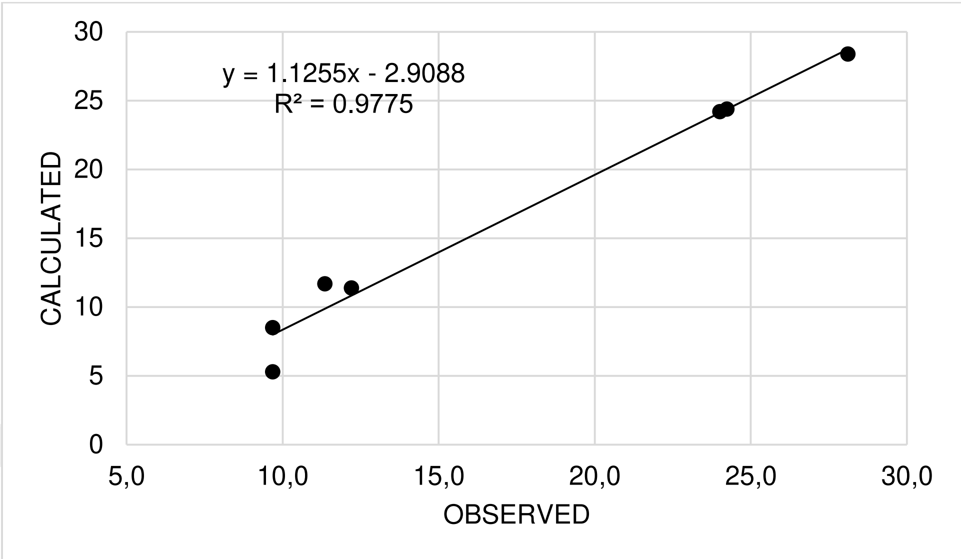


Figure 4.13. Calculated versus observed head

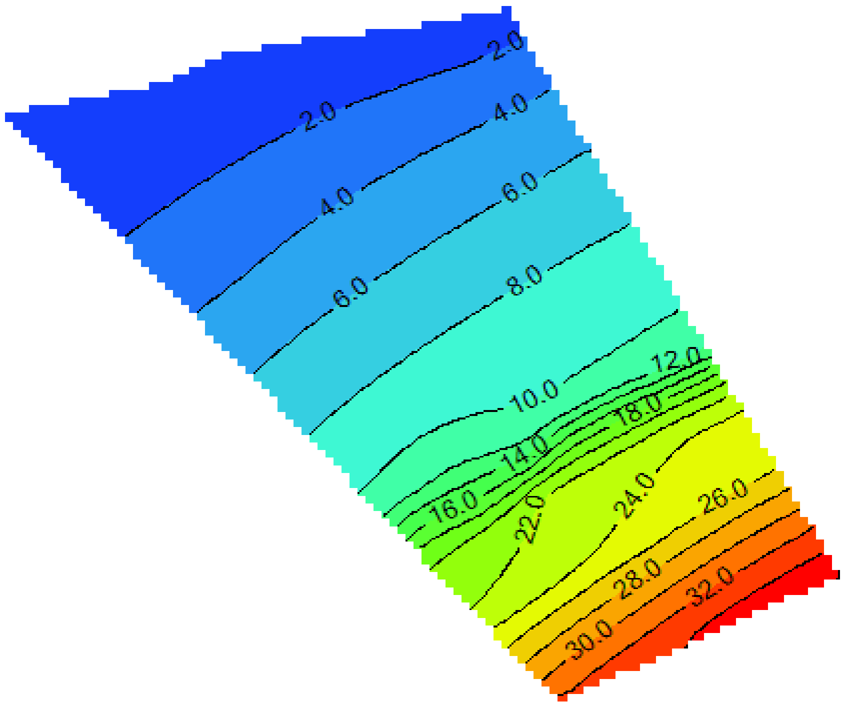


Figure 4.14. Simulated contour map of steady state (2013) of the Bosaso plain

4.4.1 Water Balance

The steady state water mass balance calculated by MODFLOW using field data available on year 2013 is given in Table 4.4.

Table 4.4. Groundwater budget for Steady state

Budget term	Cumulative Flow m^3/d
IN	
Specified flow	85001.6953
Total IN	85001.6953
OUT	
Constant head	77000.5000
Wells	8000.2002
Total OUT	85000.7002

4.5 Simulation of Seawater Intrusion in Bosaso Plain

To simulate seawater intrusion in Bosaso plain SEAWAT program was utilized under a transient condition. Firstly, SEAWAT parameter was assigned as shown in Table 4.5. Then, all cells representing the shoreline of the Gulf of Aden in the north of the Plain were assigned constant concentration with TDS of 35000 mg/l. Recharge concentration was assumed 0 mg/l since the source of salinity is from the sea. SEAWAT was calibrated using TDS concentration measured in 2013. The hydraulic conductivity and longitudinal dispersion were adjusted until the best match between the observed and simulated concentration was achieved. Good match between the observed and simulated concentration has been obtained as shown in Figure 4.15. Furthermore, Table 4.5 displays residual error between observed and simulated concentration and its summary of calibration statistics with the residual mean of concentration -5 mg/l. A determination coefficient of 0.99 and RMS 2.64 % were obtained which indicated a good match between the observed and simulated head. The model does not need any further calibration and is ready for future prediction simulation.

Table 4.5. SEAWAT model input parameters for the study area

Parameter	**value**
Freshwater density	1000 kg/m^3
Seawater density	1025 kg/m^3
Seawater concentration	35000 mg/l
Total porosity	0.3
Specific storage	0.30
Specific yield	0.20
Longitudinal dispersion	60m
Horizontal transverse dispersion	0.6m
Vertical transverse dispersion	0.1m
Density/Concentration slope	0.7143
Recharge concentration	0 mg/l

Figure 4.16 shows the simulated TDS concentrations distribution of groundwater in 2013. It can be seen that the aquifer is already affected by seawater intrusion and it extended into 5700 m inland. It is clear that seawater intrusion reaches first five wells with high salinity between 1500- 6000 mg/l. TDS concentration of the rest of the wells reached less than 1500 mg/l. The relatively high seawater intrusion is attributed due to over pumping and aquifer geometry.

Table 4.6. Residual error between observed and calculated heads

Target well	Observed TDS (mg/l)	Simulated TDS (mg/l)	Residual TDS (mg/l)
B1	6887.4	7159	-271.55
B2	3585.3	3383.5	201.8
B3	2778.3	2800.6	-22.3
B4	1541.4	1414.8	126.63
B5	1157.6	1190.7	-33.124
B6	1115.2	972.84	142.36
B7	1042	1052.2	-10.168
B8	981.16	968.82	12.34
B9	957.33	937.6	19.732
B10	964.45	953.08	11.375
B11	996.72	972.97	23.746
B12	2393.8	2811.8	-417.99
B13	1316.7	1164.8	151.91
B14	6887.4	7159	-271.55
Min. Residual			-10.2
Max. Residual			-418
Residual mean			-5
Abs. Residual mean			111.16
Standard error of the estimate			164.43
Normalized RMS			2.64 %

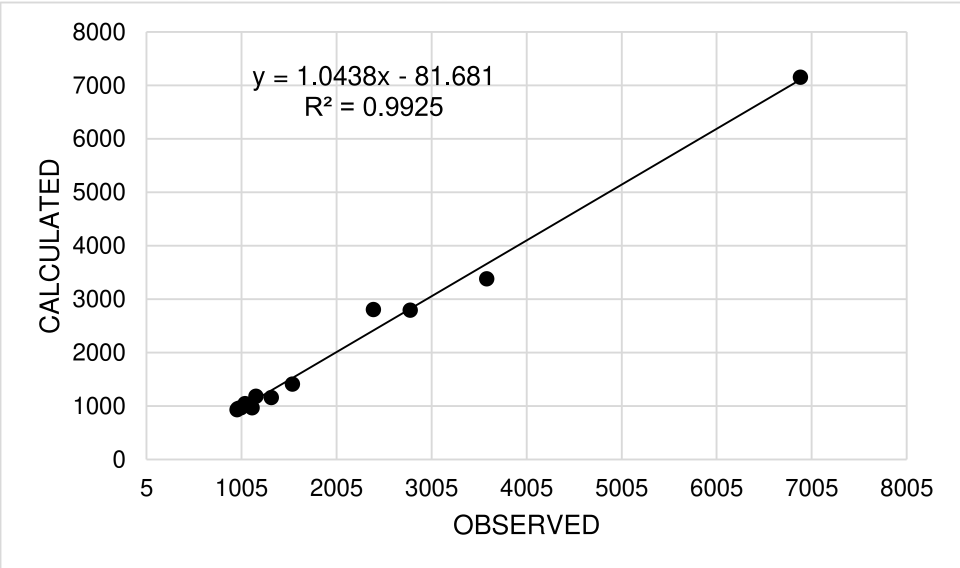


Figure 4.15. Calculated versus observed concentration of TDS (mg/l)

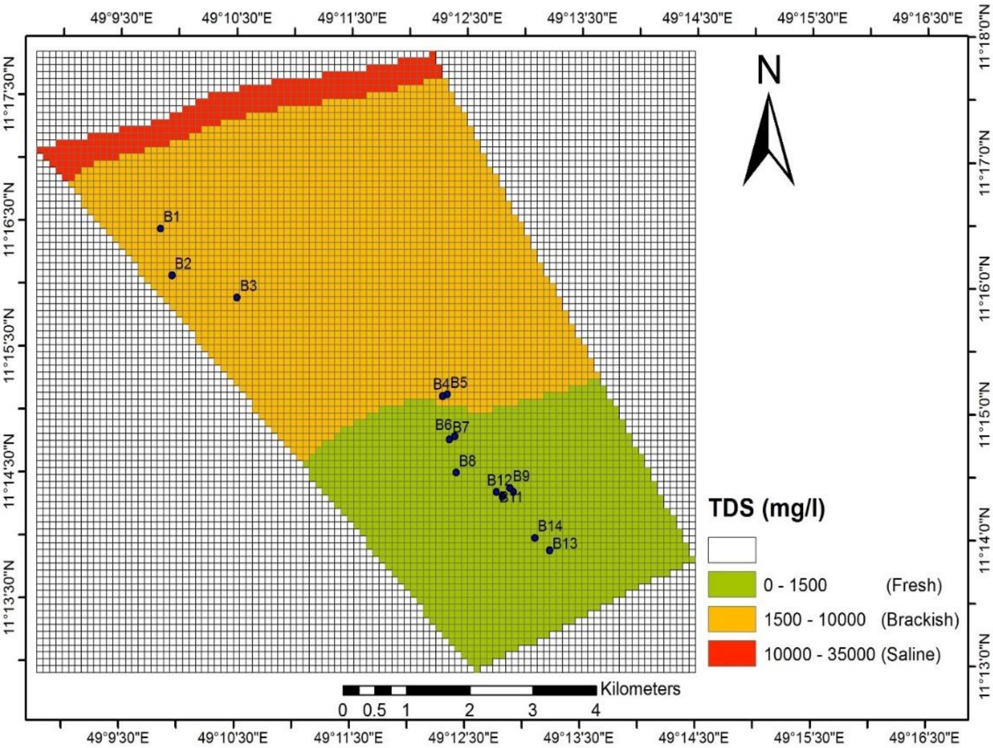


Figure 4.16. Simulated groundwater TDS concentration for year 2013

4.6 Prediction of Seawater Intrusion Under Different Management Scenarios

The calibrated of SEAWAT model was used to predict various management scenarios to identify the effects of excessive groundwater withdrawal from the coastal aquifer. The recharge rate has been taken in all scenarios as it was in 2013 except in 4th scenario was climate change effect has been considered. Four different scenarios were carried out to simulate the extent of seawater intrusion in Bosaso plain for the years 2013-2040.

1. The first scenario : the present pumping rates was maintained. The exploitation volume 2920000 m^3/day till 2040.
2. The second scenario: to satisfy maximum water demands for Bosaso city 8176000 m^3/year till 2040.

3. The third scenario : the pump rate of second scenario and climate change effect has been considered till 2040.
4. The fourth scenario: the groundwater pumping rate is reduced by 50% 5840000 m^3/year till 2040

Groundwater which contains TDS up to 1500 mg/l can be considered as freshwater and can be used for water supply. It should be noted that the extent of seawater intrusion in the Bosaso aquifer changes from scenario to scenario. The model result of the first scenario indicate that the concentration is increasing as it approaches the shoreline as expected as shown in Figure 4.13. When compared to the simulated concentration in 2013 the result indicated that the saline water and brackish water will move further 300 m and 500 m inland respectively in 2040. In this scenario the seawater intrusion would not reach new wells but shows gradually increasing of salinities until 2040 if the current extraction rates are maintained.

Predicted model results of the second scenario indicated that the simulated seawater intrusion will continou to spread further inland by reaching two new municipal wells which will make the total of 7 affected municipal wells as shown in Figure 4.14. The wells were affected by first scenerio their TDS concentration were increased. For instance, well B3 had TDS concentration 3286 mg/l in the first scenario and an increased 3377 mg/l in the second scenerio. Furthermore the width of saline water was moved from 500 m to 700 m where the width of brackish water moved from 5700 m to 6200 m in 2013 to 2040, respectively. The results of third scenario when climate change effect was considered the model results revealed nomial change in the extent of seawater intrusion when compared scenerioa two.The results of fourth scenario, by reduced 50% pumping rate shows slow progress of goundwater qaulity recovery as shown in Figure 4.16. The predicted results revelad that the two wells will become freshwater.

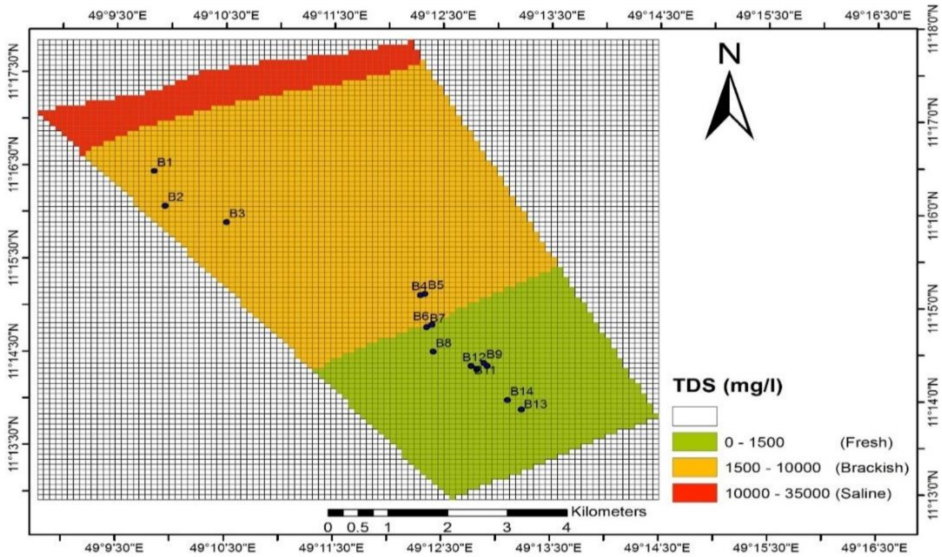


Figure 4.17. Predicted groundwater TDS concentration for year 2040 under scenario 1

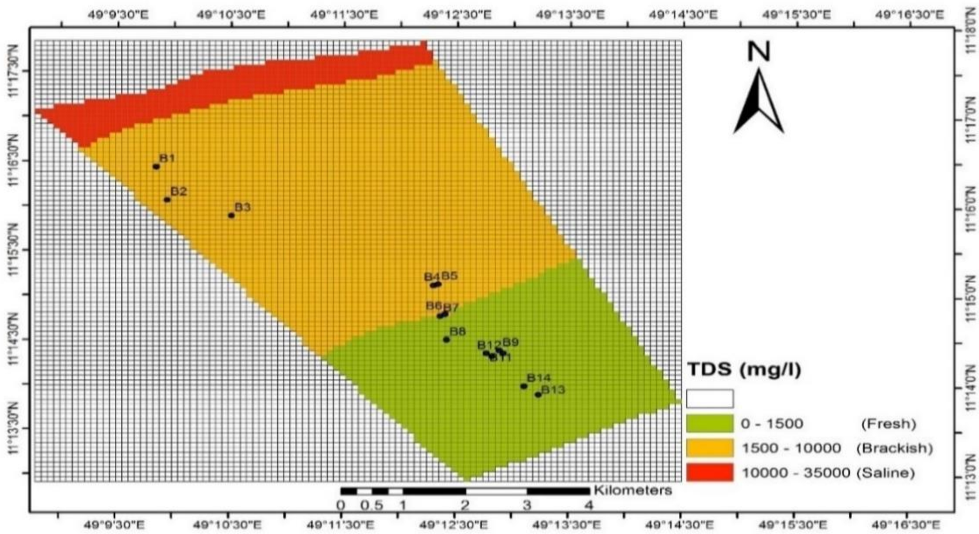


Figure 4.18. Predicted groundwater TDS concentration for year 2040 under scenario 2

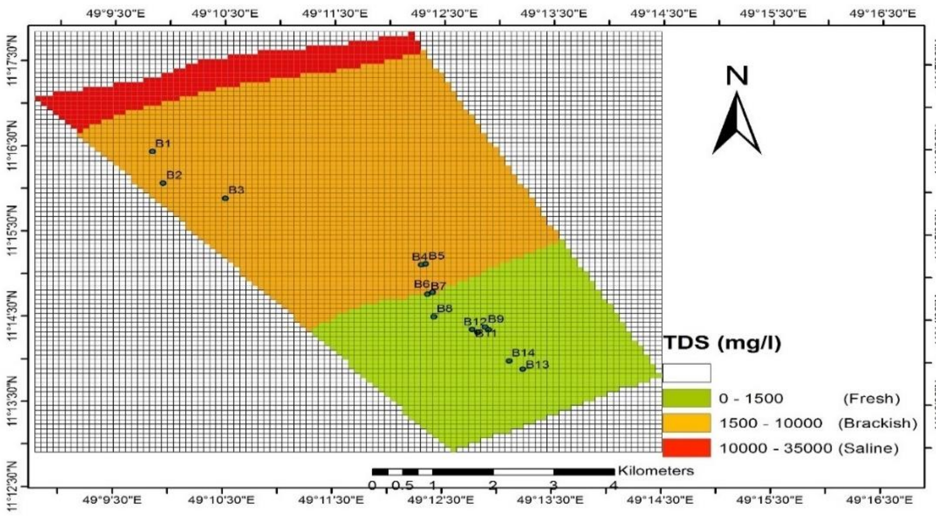


Figure 4.19. Predicted groundwater TDS concentration for year 2040 under scenario 3

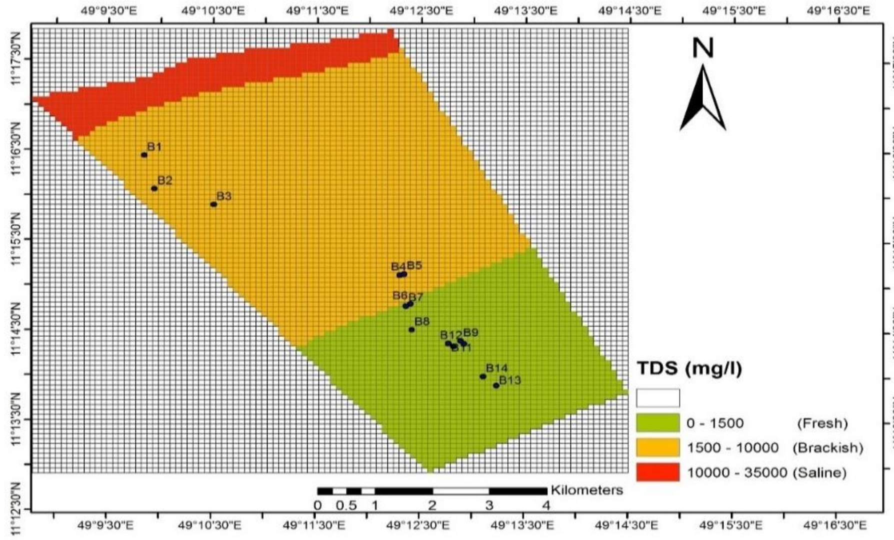


Figure 4.20. Predicted groundwater TDS concentration for year 2040 under scenario 4

5. CONCLUSIONS

Bosaso plain aquifer is more vulnerable to the seawater intrusion due to deficiency of rainfall and over withdrawal to meet the city water demand. The objective of this study was to model the potential effect of seawater intrusion into the coastal aquifer of Bosaso Plain. The variable density flow code (SEAWAT) was used to determine how far inland seawater intrusion has moved and to predict the future extend. The conceptual model was developed by using geological and hydrogeological information in the Bosaso Plain then the conceptual model was converted into a numerical model using finite difference method. Afterwards, the Model was calibrated using automated parameter estimation code (PEST) by adjusting hydraulic conductivity until the reasonable match between the observed and simulated heads and concentration were obtained. Statistical error criteria such as root mean square (RMS) have been used to evaluate the calibrations. Good match between the observed and simulated head and concentration values was achieved. The model prediction was carried out of 27 years until 2040 based on calibrated model.

To evaluate the effects of groundwater pumping on seaweatr intrusion in th e Bosaso plain, the simulations in the four management scenarios was conducted. The first scenario will induce further seawater intrusion into aquifer. The simulation results revealed the interface will move about 6 km inland and that concentration of TDS in municipal wells will continue to increase until 2040. The second scenario was the worst case and will accelerate the seawater intrusion by affecting 7 municipal wells and extending seawater interface to 6.2 km inland. It can be concluded that the water demand projected in 2040 would lead further seawater intrusion Furthermore, the fourth scenario by reducing 50 % of pumping rate shows positive impact into aquifer by preventing any further seawater intrusion and slowly reducing salinity. Overall, based on model predictions, it is evident that increased pumping rate will lead to further seawater movement into Bosaso Plain aquifer.

On the other hand, the hydro-chemical water quality results show good agreement with the model results and revealed most of groundwater in the study area is unsafe for drinking purposes due to salinization by seawater intrusion, except in the wells located far inland (Biyo Kulule) which are safe for drinking.

5.1 Recommendations

The following recommendation can be made of this study.

- This study is a useful example of modelling seawater intrusion in the coastal aquifers. The SEAWAT model reveals to be an effective and robust simulation tool for variable-density flow and transport in porous media.
- There should be adequate investment to ensure continues groundwater monitoring in the study area.
- The excessive pumping of groundwater lead to further intrusion of seawater intrusion into the aquifer. Therefore, it is necessary to stop the continuous deterioration of water quality of the aquifer by finding alternative sources such as seawater desalination plants or artificial recharge.
- All wells located in the contaminated area must be closed to avoid further seawater intrusion or can used as injection wells.
- Bosaso water authority must pursue strategic plan to use additional water resource to meet future water demand as increasing water demand leads deterioration of groundwater quality.
- The model should be updated to increase its simulation accuracy as new data become available.

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