

**MODELING CLIMATE CHANGE IMPACT ON SEAWATER
INTRUSION IN THE COASTAL AQUIFER OF THE
EASTERN PROVINCE OF SAUDI ARABIA**

BY

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Dedication

To my family and wife, whose prayers were with me all the time, and without their encouragement and support, I might not be able to accomplish this thesis.

To my instructors and professors for their teaching and guidance

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"In the name of God, the most gracious, the most merciful"

We thank God, first and last, for what enabled us to achieve this achievement, and for making it easy for us to write this master's thesis at King Fahd University of Petroleum and Minerals.

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LIST OF ABBREVIATIONS

2D	:	Two Dimensional Seismic
SEAWAT	:	a generic computer-based program for the simulation of variable density in different dimensions of groundwater flow.
TDS	:	Total Dissolved Solid
PPM	:	Parts Per Million
TRPT	:	Ratio of horizontal transverse dispersion to longitudinal one.
TRVT	:	Ratio of vertical transverse dispersion to longitudinal one.
DMCOEF	:	Effective molecular diffusion coefficient
AAP	:	Average Annual Precipitation
KSA	:	Kingdom of Saudi Arabia

ABSTRACT

Full Name : Obada Ahmad

Thesis Title : MODELING CLIMATE CHANGE IMPACT ON SEAWATER
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Coastal aquifers are important in supporting ecosystems, providing freshwater resources for human consumption, and sustaining agriculture. Climate change has profound impacts on coastal aquifers, primarily due to its potential to cause sea level rise and variations of rain -precipitation- from one place to another around the world. These impacts introduce challenges such as the intrusion of seawater into the aquifers, consequently altering their chemistry. Generally, there is limited research on the hydrogeological and environmental conditions of the Eastern province of Saudi Arabia and more specifically on the issue of seawater intrusion. . There is a need to develop accurate models to understand this phenomenon and its links to climate change, to mitigate its impacts. This study aims to understand seawater intrusion in the Eastern Province of Saudi Arabia, particularly regarding the long-term impacts of climate change on this phenomenon. In this study, this gap has been addressed using climate change models to anticipate the extent of saltwater encroachment in the area, up to the year 2100. A density-dependent transport model (SEAWAT) with three different scenarios (SC1, SC2, and SC3) has been used to simulate the saltwater encroachment phenomena. The input data of sea level rise (SLR) were 0.58, 0.70, and 0.91m for SC1, SC2, and SC3, respectively. The inserted data of recharge rates to the climate models have varied from 4.5 to 5.89 mm/yr depending on the model scenario.

This results in shifting the interface of saltwater and freshwater, further inland. The horizontal extent of saltwater has reached.

To address this issue, a management strategy is proposed, including adaptive water management plans, like reducing the extraction of groundwater, and merging the later solution with injection wells. Implementation of these measures have showed the reduction of impacted saline-area in the aquifer and shifting back the current saltwater-freshwater interface by 12.64% towards the shoreline.

ملخص الرسالة

الاسم الكامل: عبادة وليد محمد أحمد.
 عنوان الرسالة: نمذجة تأثير تغير المناخ على تداخل مياه البحر في طبقة المياه الجوفية الساحلية بالمنطقة الشرقية للمملكة العربية السعودية.
 التخصص: علوم البيئة.
 تاريخ الدرجة العلمية: كانون الأول من عام ٢٠٢٣م، الموافق جمادى الآخرة من عام ١٤٤٥هـ.

تعتبر طبقات المياه الجوفية الساحلية مهمة في دعم النظم البيئية، وتوفير موارد المياه العذبة للاستهلاك البشري، واستدامة الزراعة. لتغير المناخ آثار عميقة على طبقات المياه الجوفية الساحلية، حيث أنه مع ارتفاع مستويات سطح البحر وتغير أنماط هطول الأمطار، يؤثر تغيير المناخ بشكل مباشر على المياه الجوفية الساحلية ويطرح تحديات كبيرة مثل تداخل مياه البحر باتجاه المياه الجوفية. تمت دراسة طبقات المياه الجوفية الساحلية في المنطقة الشرقية من المملكة العربية السعودية باستخدام نماذج تغير المناخ لتوقع مدى تداخل المياه المالحة في المنطقة حتى عام ٢١٠٠.

تم استخدام نموذج النقل المعتمد على الكثافة (SEAWAT) بثلاثة سيناريوهات مختلفة (SC1، SC2 و SC3) لمحاكاة تأثيرات تغير المناخ على تسرب مياه البحر في المنطقة الشرقية من المملكة العربية السعودية. تظهر الدراسة أن ارتفاع مستوى سطح البحر والتغيرات في أنماط هطول الأمطار تؤثر بشكل كبير على حركة المياه الجوفية ومياه البحر المالحة حيث تدفع الواجهة إلى الداخل أكثر. في السيناريوهات النمذجية، تظهر مستويات سطح البحر التي تتراوح من ٠,٥ إلى ٠,٩١ مترًا تأثيرًا كبيرًا لـ SLR على واجهة تسرب مياه البحر. يُظهر هطول الأمطار الذي يتراوح من ٧٪ إلى ٢٧٪ من المتوسط الحالي البالغ ٩٠ ملم/عامًا تأثيرًا منخفضًا لـ SLR على واجهة تسرب مياه البحر. ولمعالجة هذه المشكلة، تم اقتراح استراتيجية الإدارة، بما في

ذلك خطط إدارة المياه التكيفية، مثل تقليل استخراج المياه الجوفية، ودمج الحل اللاحق مع آبار الحقن. وقد أظهر تنفيذ هذه التدابير انخفاض المنطقة المالحة المتأثرة في طبقة المياه الجوفية وإعادة الواجهة الحالية للمياه المالحة والمياه العذبة بنسبة ١٢,٦٤٪ نحو الخط الساحلي.

CHAPTER 1: INTRODUCTION

1.1. Coastal Aquifers Importance

Although surface water is well known to be important due to its numerous applications in various sectors of daily life, groundwater is becoming more important as a reliable water resource in drought-prone areas. Groundwater is used as a primary source of irrigation, particularly in arid regions such as Saudi Arabia. [1] Coastal aquifers are considered primary freshwater sources for highly populated regions and crucial ecosystems. [2]. They are considered a critical source of water for over 2 billion people around the world, [3] but they face high stress due to rising demands. [4]

Human activities, including improper management of organic and inorganic waste, contribute to groundwater pollution, posing an additional stressor on coastal aquifers [5]. Various sectors such as industry, agriculture, and commerce significantly impact groundwater quality. Additionally, excessive well extraction, driven by rising water demands, often exceeds the regenerative capacity of coastal aquifers, leading to saltwater encroachment into freshwater [6,7]. Consequently, understanding and mitigating seawater intrusion is essential for preserving the integrity and sustainability of coastal aquifers. This phenomenon will be elaborated upon in the next section.

1.2. Seawater Intrusion

Seawater intrusion (SWI) is defined as the process of seawater entering and infiltrating coastal lands.[8] This natural phenomenon is a significant environmental problem that affects both the sustainability and the quality of coastal aquifers [9,10]. Factors such as excessive pumping of groundwater, either for agricultural, industrial, or residential purposes, disturb the balance between fresh and saline water [11]. Other factors, such as lack of natural recharge, and climate variations, contribute to seawater expansion as global temperatures rise. Rising sea levels raise hydraulic

pressure, pushing the saltwater/fresh groundwater interface further inland. [11,12] One example is the decline in groundwater levels and limited rainfall led to the intrusion of seawater, transforming previously available sources of freshwater into a saline belt along the coast of Gujarat. [13] Consequently, as of 1976, this salinity intrusion has impacted more than 770 villages, covering an area of 1.65M hectares and affecting more than 1.33 million people. [13]

Climate change can positively or negatively impact the intrusion phenomena. As rainfall patterns differ globally, the consequences of climate change on precipitation exhibit similar variability. Climate change, influencing wind patterns and ocean currents, will also reduce precipitation in certain regions. Storm surges could result from variations of ocean currents and pushes seawater inland, increasing the intrusion in coastal areas, and impacting surface water and groundwater quality. [14] Furthermore, elevated temperatures, another consequence of climate change, increase surface water evaporation, potentially resulting in increased precipitation in other areas, as well as increasing salinity of both freshwater and groundwater. [15]

1.3. Climate Change Impacts on Coastal Aquifers

Climate change concerns long-term alterations in Earth's typical weather patterns, affecting temperature, precipitation, and wind dynamics. This results from both natural variations and human-induced changes to the climate system. Notably, climate change is characterized by rapid and substantial global warming, primarily driven by human activities such as the release of greenhouse gases (GHGs) from burning fossil fuels, deforestation, and industrial processes. This anthropogenic influence traps heat, causing an increase in the surface temperature of Earth, and fundamentally altering climatic conditions [16-17].

This widespread climate change has far-reaching implications for ecosystems, resulting in shifts in species abundance and population dynamics [18]. Moreover, it leads to a global rise in

temperatures and an escalation in the frequency of extremely hot days across diverse regions of the world [19].

The profound impact of climate change extends to coastal aquifers, unleashing many adverse consequences. These include rising sea levels, the submergence of land, deterioration of groundwater quality, intensified salinization, and the depletion of aquifers. This intrusion not only results in land loss but also critically diminishes the availability of precious freshwater resources [20].

Moreover, climate change may reduce groundwater recharge rates and increase the demand for freshwater, by impacting various components of the water cycle, affecting the availability and distribution of freshwater. These changes can result in increased demand for freshwater resources across different sectors and amplify the vulnerability of coastal aquifers. [21].

To address this growing challenge, it is crucial to adopt a wide range of sustainable mitigation and adaptation measures. These include managed aquifer recharge, treated wastewater use, and improved irrigation efficiency [22]. A tool for sustainable resource management is understanding aquifer status through modeling. This helps visualize the extent of saltwater intrusion, enabling the formulation of efficient mitigation strategies.

To address climate change impacts on the coastal aquifers, the next section will explain in detail the modeling of seawater encroachment for better understanding and predicting the extent of the problem. Thus, developing efficient mitigation strategies for the sustainable management and protection of these coastal aquifers [23].

1.4. Modeling of SWI

The pioneering work in SWI analysis can be traced back to the foundational concepts introduced by Willem Badon-Ghyben and Alexander Herzberg in 1901, known as the Ghyben–Herzberg relation [24]. These early formulations marked a milestone in the field of hydrogeology by offering analytical solutions to model and predict the dynamics of seawater intrusion into coastal aquifers.

Fig. 1 illustrates the seawater encroachment phenomena, demonstrating that the column weight of freshwater, all the way from the water table to the interface, equals the weight of the saltwater column, extending from sea level to the same depth. Equation (2.1) shows the height of the freshwater column:

$$h = z + b_f \quad (2.1)$$

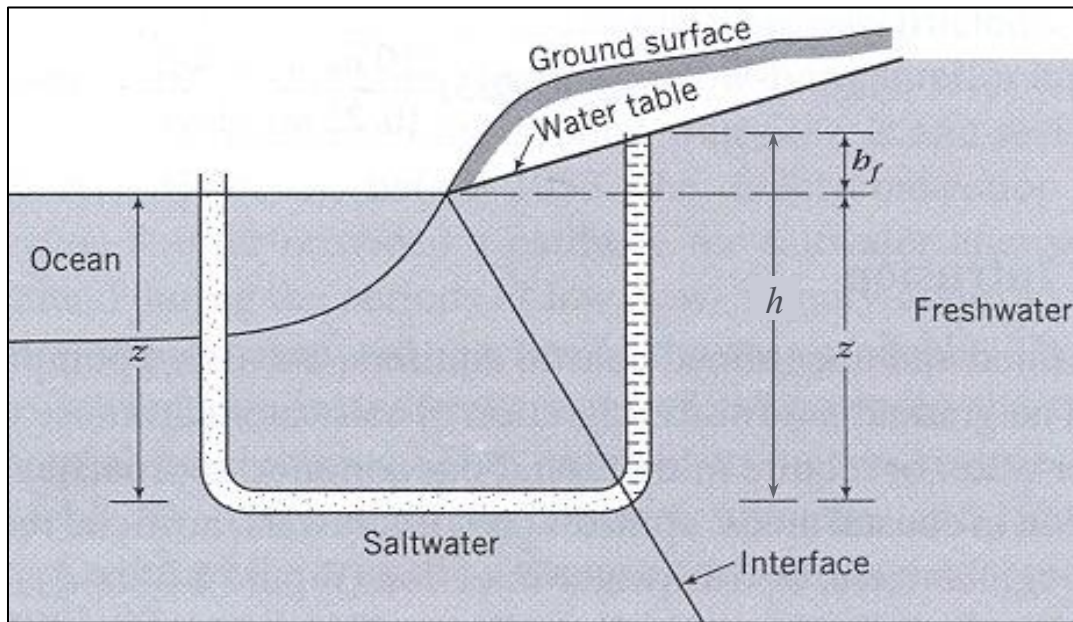


Figure 1. Seawater Encroachment Phenomena [25].

Where (b_f) is the freshwater elevation above sea level, and (z) is the length between sea level and interface. Thus, the sum of (z) and (b_f) gives the total height of the freshwater (h) above the saltwater/freshwater interface and are explained graphically in Fig. 2.

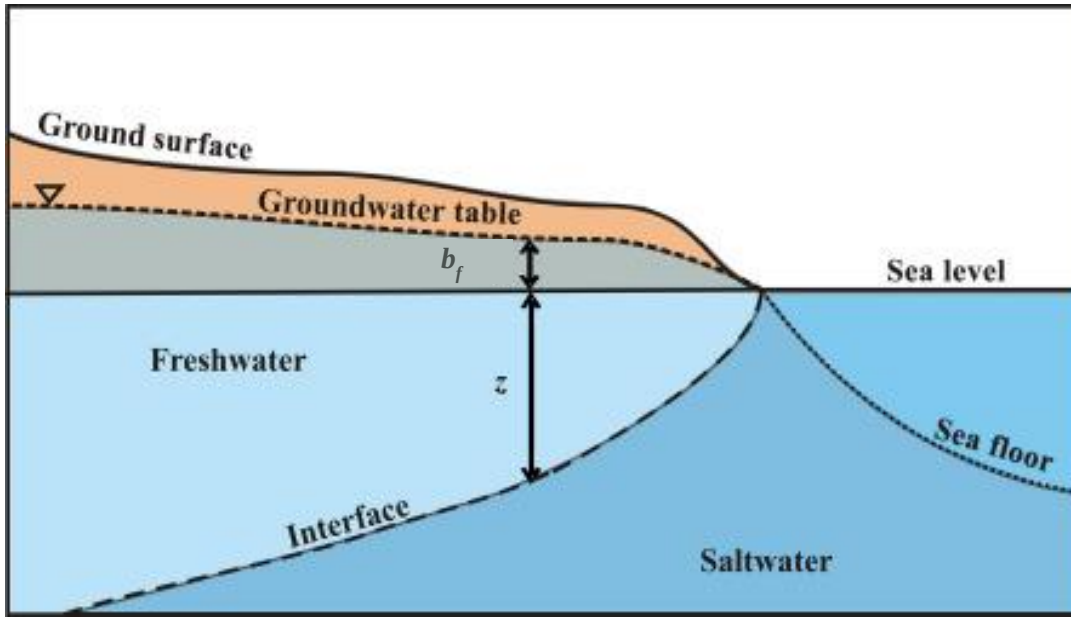


Figure 2: Ghyben–Herzberg Relation [24]

Assuming that (ρ_s) represents saltwater density and (ρ_f) is the freshwater density, equating both thicknesses will result in:

$$h * \rho_f = z * \rho_s$$

substituting Eq. 2.1 in (h) :

$$(z + b_f) * \rho_f = z * \rho_s$$

$$z = \frac{\rho_f}{(\rho_s - \rho_f)} h \quad (2.2)$$

Ghyben–Herzberg relation, connects and balances (b_f) and (z) with their densities, as shown mathematically in equation (2.2), where the (ρ_s) and (ρ_f) are saltwater and freshwater densities, respectively.

Freshwater typically has a density of approximately $1.000 \text{ (g/cm}^3\text{)}$ at $20 \text{ }^\circ\text{C}$, while seawater's density is roughly 1.025 g/cm^3 . Substitution of these values in equation (2.2) results in a simplified ratio named the Ghyben–Herzberg ratio, shown in equation (2.3) as follows:

$$z = 40 b_f \quad (2.3)$$

According to the Ghyben-Herzberg ratio, there are roughly forty meters of freshwater below sea level for every meter of freshwater above sea level. It should be mentioned that the assumptions used to create these early models simplified the actual complexity of aquifer systems. [26].

1.5. Study Area

The eastern coastal aquifer in Saudi Arabia is part of the larger sedimentary basins in the Arabian Peninsula, which consists of different sub-aquifers with varying hydraulic properties [27]. These aquifers are potentially affected by various environmental issues, including chemical contamination, seawater intrusion, and salinization [28].

The eastern coastal aquifers in Saudi Arabia are Neogene, Alat, and Khobar aquifers, as illustrated in Figure 3. Each aquifer has a different depth and hydraulic characteristics [27]. Numerous studies in this field have focused on acquiring meteorological data, such as precipitation and temperature, alongside hydrogeological data like hydraulic conductivity. The Transmissivity of the Alat aquifer varies from $2.6 \times 10^{-5} \text{ m}^2/\text{s}$ to $5.1 \times 10^{-3} \text{ m}^2/\text{s}$, knowing that the depth ranges from 30-40m, with 25m thickness of porous limestone around the coastal area. Assuming an average hydraulic conductivity of $3 \times 10^{-5} \text{ m}^2/\text{s}$ for both Neogene and Dammam Aquifers (as shown in Table 1) will be used later in the modeling [39]. Al-Khobar aquifer is essential, as its water is utilized for irrigation in regions like Al-Hassa and Qatif. This aquifer is characterized by fractured limestone with an 80m thickness and a depth of around 130m, with a transmissivity ranging from $0.9 \times 10^{-2} \text{ m}^2/\text{s}$ to $0.29 \text{ m}^2/\text{s}$ [28].

The porosity of the Dammam aquifer in Saudi Arabia varies based on the specific location. In Kuwait, the porosity varies from 4 to 35% [29]. The Upper Dammam Formation in Kuwait has a

porosity range from 30% to 53% [30]. In the Umm er Radhuma limestone aquifer in Saudi Arabia, the effective porosity is reported to be 30% [31], while for the Khobar aquifer, the porosity ranges from 30% to 33% [32].

Several studies were done to assess the salinity levels, contamination mechanisms, and human health risks associated with coastal aquifers [33-35]. The water quality in these aquifers is poor and unsuitable for drinking, posing health risks to the population, especially infants and children [36]. Seawater intrusion is a major concern in the region, leading to increased salinity and further deteriorating the groundwater quality, making the need for proper management practices to protect freshwater resources a necessity [37].

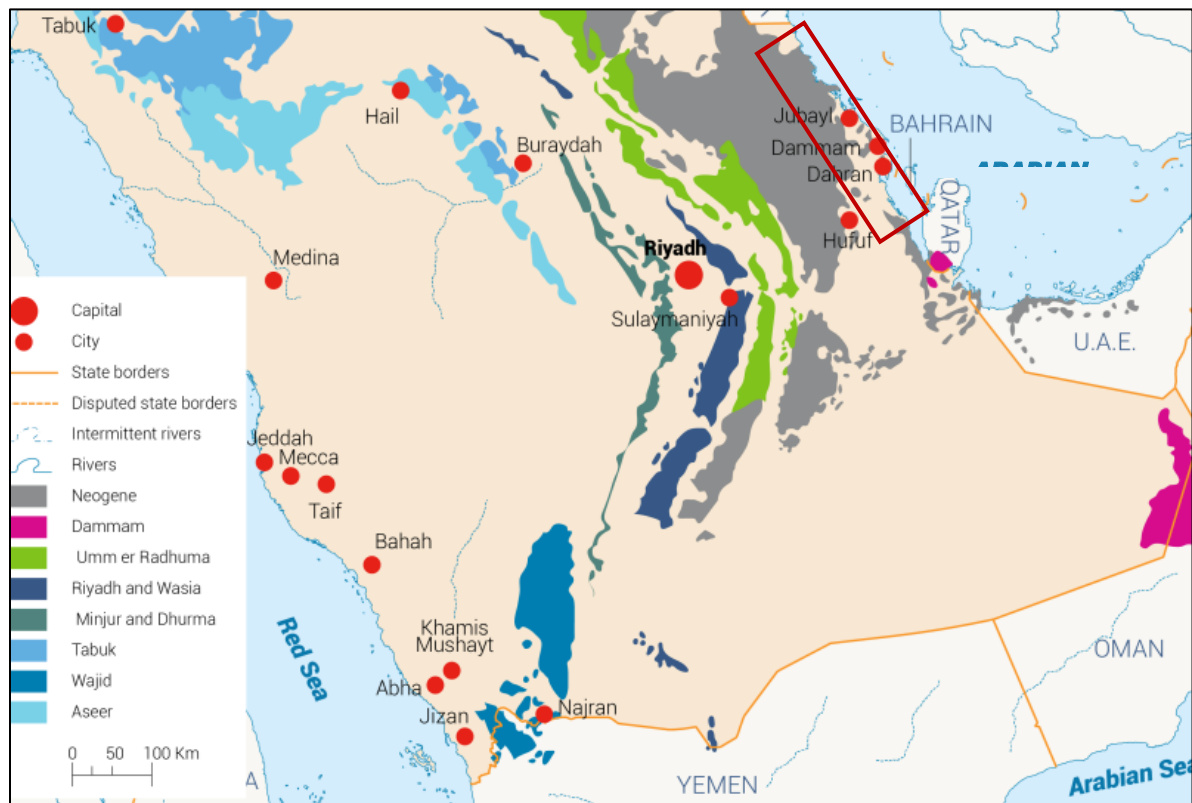


Figure 3: Related Aquifers in Study Area [38]

Table 1. Hydrological Settings in the Neogene & Dammam Aquifers [39]

Age	Formation	Thickness (m)	Aquifer	Hydraulic Conductivity [m/s]		Storage Coefficient [-]		Specific Yield [%]	
				Range	Rep. Value	Range	Rep. Value	Range	Rep. Value
Neogene	surface deposits		Neogene	From 1×10^{-7} to 1×10^{-2}	3×10^{-5}	From 1×10^{-5} to 1×10^{-3}	1×10^{-5}	1 - 7	1
	Hofuf	140 - 500							
	Dam								
	Hadruk								
Paleogene	Dammam	120 - 450	Dammam	From 1×10^{-6} to 1×10^{-2}	3×10^{-5}	From 9×10^{-5} to 8×10^{-4}	1×10^{-4}	1 - 5	1
	Rus	100 - 270							
	Umm er Radhuma	405 - 800	Umm er Radhuma	From 1×10^{-7} to 1×10^{-2}	2×10^{-5}	From 1×10^{-4} to 1×10^{-3}	1×10^{-4}	1 - 7	2

1.6. Objectives

The main objective of this study is to clarify the extent of the impact of climate change on seawater intrusion into coastal aquifers in the eastern region of the Kingdom of Saudi Arabia. This objective will be achieved through a density-dependent flow model (DDFM). This model will assist in mitigating the adverse effects of seawater intrusion by examining several climate change scenarios, in addition to provide recommendations to enable decision-makers to take radical measures to reduce these risks because of their significant impact on the region. The specific objectives of this study are the following:

1. Interpret the coastal aquifers of the Eastern Province of Saudi Arabia through developing the conceptual, and numerical groundwater flow models.
2. Study the movement of saltwater encroachment into the coastal aquifers in the study area by building a seawater intrusion model for the Easter Province aquifer.
3. Determine the climate change impacts (sea level rise and recharge rates) on seawater intrusion in the aquifer, using a density-dependent flow model.
4. Testing various scenarios of climate change impact using the developed model to produce actionable recommendations for the Eastern Province aquifer.

There are five chapters in this study. An overview of seawater intrusion and coastal aquifers is given in the first chapter. The second chapter reviews the literature on modeling the effects of climate change on coastal aquifers and how such changes are affecting Saudi Arabia's eastern province. The third chapter provides more details on the study's methodology, and the fourth chapter provides examples of the outcomes of various climate scenarios. The study's conclusions and a list of recommendations for the relevant governmental authorities are provided in the last chapter.

CHAPTER 2: LITERATURE REVIEW

Seawater intrusion is a serious problem threatening freshwater resources and ecosystems near coasts, and it can lead to water scarcity issues and negatively impact agricultural productivity [40]. This phenomenon was first recognized and documented in the late 19th century on Long Island, New York [41]. Its global prevalence includes coastal areas of California in the United States, Mediterranean countries like Spain and Italy, Southeast Asian nations such as Vietnam and Thailand, as well as Middle Eastern countries like Egypt and Saudi Arabia [42-44].

The coastal aquifer in the Eastern Province of Saudi Arabia is most vulnerable to seawater intrusion due to climate change and high pumping rates [40]. It is essential to understand and predict the impacts of seawater intrusion. With a focus on the Eastern Province of Saudi Arabia, this review of the literature attempts to assess research results on seawater intrusion and its effects on coastal aquifers. This review aims to identify gaps in current knowledge and suggest future research options by analyzing existing studies.

One of the consequences of climate change that accelerates the problem of seawater intrusion in coastal aquifers is sea level rise (SLR) [45]. Depending on the location and rate of sea level rise, groundwater salinity is affected. Wassef and Schüttrumpf (2016) investigated the rise in sea level in Egypt. They expected that SLR would increase salinity concentration in coastal aquifers to reach 5000 mg/l [46]. In South Florida, Guha and Panday (2012) estimated that a 0.6 m increase in sea level is likely to increase chloride concentrations in groundwater wells by 100-600% [47]. The rate of sea level rise in Salento, Italy will result in a maximum sea level rise of approximately 2m during the 22nd century. The increase in sea level will cause a depletion of available groundwater discharge, as much as 16.1% [48].

The effects of climate change vary from one country to another. For a better understanding of the variation of climate change, scientists have developed conceptual and methodological frameworks named Shared Socioeconomic Pathways (SSP) [49,50]. These are a set of consistent socio-economic assumptions that explore the potential shifts in global society, demographics, and economics in the coming century. SSP's have been employed into six different Integrated Assessment Models (IAM) for predictions of future energy usage patterns and greenhouse gas emissions. The SSP's scenarios are important for understanding the potential range of future climate change outcomes and for informing policy and decision-making processes [51,52].

To understand the impact of climate change on the extent of saltwater encroachment into coastal aquifers, scientists have used climate change models., Numerical modeling tools based on modeling variable density flow (i.e. SEAWAT [53]) provide valuable insights and enable scientists to predict future intrusion levels, assess and manage associated risks, optimize water management strategies, and ultimately improve decision-making related to coastal resource management [54].

Numerical modeling has been used to study seawater intrusion in different countries. For instance, in China, Wang et al. (2023) developed a SEAWAT model for the Dagu River Basin [55], while others have employed 2D sand tanks and MODFLOW models to analyze its effects [56]. As examples of using numerical models for seawater intrusion assessment, in Florida, USA, a numerical model was developed using SEAWAT to simulate the impact of rising sea levels on seawater intrusion. The model subjected to a 10 cm increase in the hydrostatic head of saline water, representing the potential effect of sea level rise, resulted in a significant increase in simulated seawater intrusion distance (from 85.75 cm to 110 cm), with other boundary conditions and hydraulic parameters remaining unchanged [57]. In Gunsan, South Korea, different model scenarios were tested to determine the impact of sea level rise on aquifer salinity. It was found that

an increase of 40.3% of salinity compared to the baseline would occur with a 0.57 m of sea level rise, and with a rate of $0.00549 \text{ kg s}^{-1}$ for freshwater recharge [60]. This diverse range of research shows the global concern for seawater intrusion and the effects of different climate models in addressing saltwater encroachment into coastal aquifers.

In the Arabian Peninsula, researchers have studied the climate change effects on seawater intrusion, where the climate is predominantly arid and semi-arid. However, research in Oman, found that the salinized area in the Jamma aquifer will increase by 32% by the year 2050, and 38% and by the year 2070, compared to the base case back in 2015 [21]. In Bahrain, Al-Jeneid et al., (2007) found that Bahrain will lose nearly 53 square kilometers with a Only 0.5m rise in sea level, and it could reach up to 79 square kilometers for 1.5m [61].

Studies of Saudi Arabia's coastal aquifers have primarily focused on environmental problems that impact the Red Sea and the western coastal aquifers [62–64]. The water quality in the Tihama coastal plain in southern Saudi Arabia was studied by Zaidi et al. (2017) [65]. Approximately 16% of Saudi Arabia's west coast is very vulnerable to climate change, whereas 44% is considered marginally vulnerable, according to a different study by Almaliki et al. (2023) that used the coastal vulnerability index [66]. Another study looked at the effects of heavy metal contamination and SWI in the Al Qunfudhah area along the Red Sea coast [67]. Few studies have been analyzing the Arabian Gulf, but none has discussed the climate change impact on coastal aquifers.

The analysis of existing research gives valuable insights into the knowledge gaps in modeling the climate change effects of seawater intrusion in coastal aquifers. The following issues have been noticed:

- 1- limited amount of research has focused on seawater intrusion in the Eastern Province of Saudi Arabia.
- 2- The long-term effects of climate change on seawater intrusion in this region remain understudied.
- 3- The necessity of considering sea level rise in the model, to formulate the relationship of SLR with seawater intrusion for accurate modeling.
- 4- No available research has related the impacts of climate change on the seawater intrusion directly.

With these knowledge gaps, this study aims to fulfill them and address these gaps by investigating potential changes in seawater intrusion patterns under different climate change scenarios, with a particular emphasis on the unique challenges faced by the Eastern Province. Addressing these knowledge gaps in future research will contribute to more accurate and comprehensive models for managing seawater intrusion in coastal aquifers in the area.

CHAPTER 3: METHODOLOGY

The research methodology of this study is illustrated in Fig 4. The methodology begins with the acquisition of hydrogeological data from a variety of sources, including published papers, reports, and maps. Then building the conceptual model to formulate the nature of the study area. The next step will be to develop and run the mathematical model and test various scenarios. The last step will be to analyze the results and suggest recommendations to the concerned entities.

The research built on a comprehensive review of literature from diverse locations to create a unique model, focusing on the relationship between water levels and the impacts of climate change on them. The impact of climate change on sea level rise and rainfall changes will be discussed in the periods that will be studied, up to the year 2100. Three typical scenarios will be explored:

- "SC1" Scenario: Examines the most adverse projected climate change impacts on seawater intrusion, representing a worst-case scenario.
- "SC2" Scenario: represents the balanced scenario, providing a more realistic depiction of the situation, serving as an intermediate projected impact of climate change on seawater intrusion.
- "SC3" Scenario: Examines an optimistic outlook with minimal projected impacts, exploring best-case possibilities.

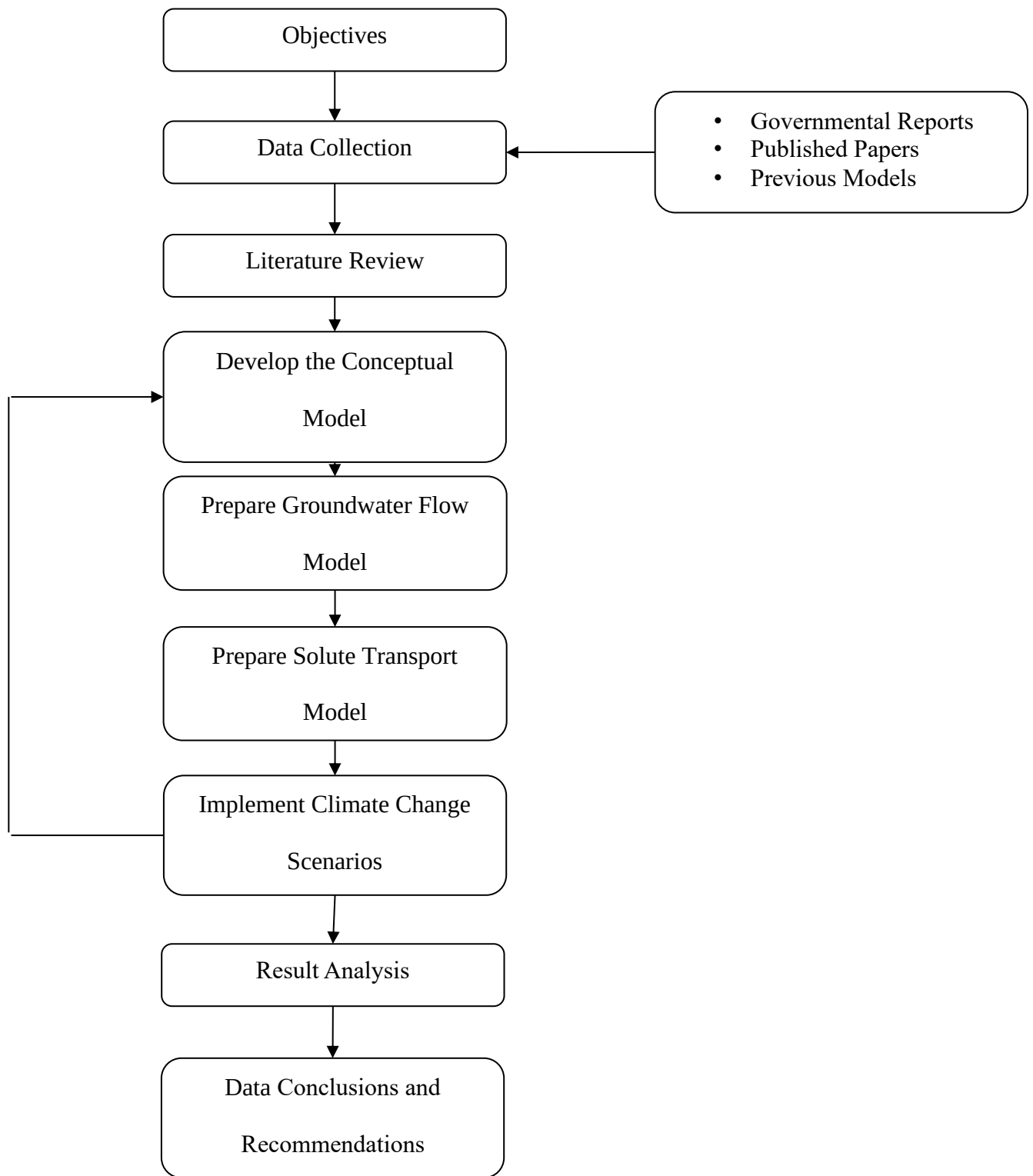


Figure 4. Research Methodology

CHAPTER 4: MODELING THE IMPACT OF CLIMATE CHANGE ON THE SEAWATER INTRUSION ON THE EASTERN PROVINCE OF KSA

4.1. Modeling Approach

This study investigates the impact of climate change on the seawater intrusion (SWI) in the Eastern Province of KSA through a comprehensive approach that combines groundwater dynamics and solute transport modeling. Initially, the conceptual model was prepared, then the hydrogeological settings and hydraulic properties are utilized to model the flow in the area. Then, the flow simulation output was used for solute transport modeling. Finally, both approaches are integrated for density-dependent groundwater flow and solute transport, providing a comprehensive representation of the system. This integrated approach ensures a more accurate simulation of real-world conditions and enhances the exploration of SWI in the study area.

4.2. Conceptual Model

The conceptual model was developed (Figure 5) to form the basis for analysis and numerical modeling. The conceptual model incorporates geology and boundary conditions to enhance the model. Steady-state conditions are assumed due to the relatively constant annual recharge and pumping rates observed in this region, and to become initial conditions for the transient periods of the model. Based on the literature, the aquifer is considered homogenous with a horizontal to vertical anisotropy factor of 1:10. The minimal spatial variations in the direction of groundwater flow, presented in Figure 6, simplify and enable the model analysis of the primary drivers of seawater intrusion in the region.

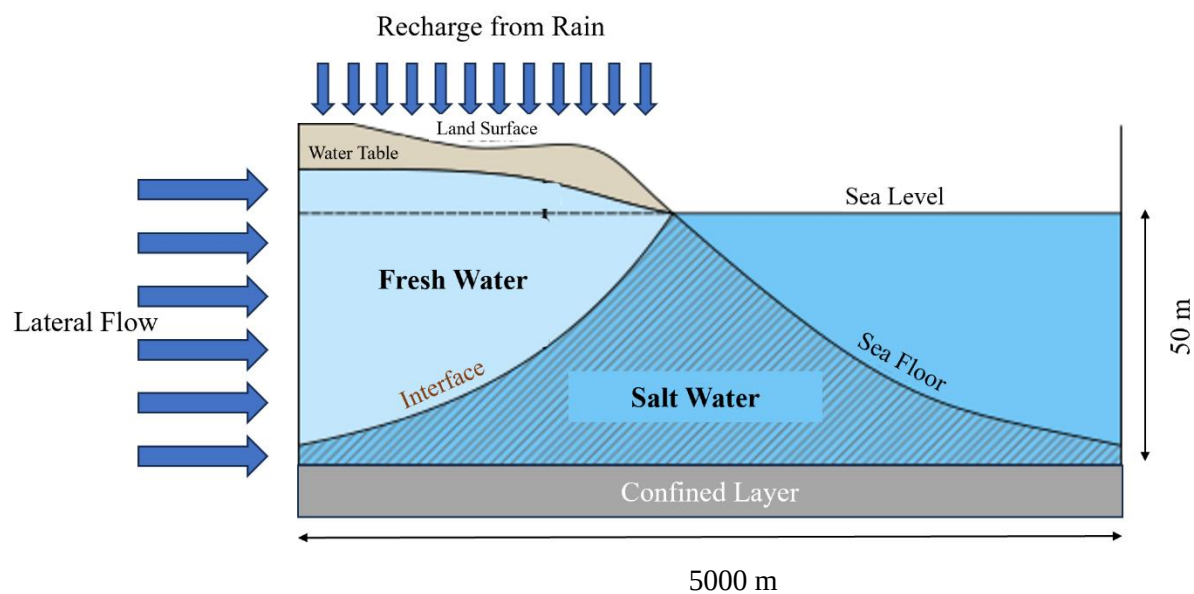


Figure 5. Conceptual Model of the Study Area.

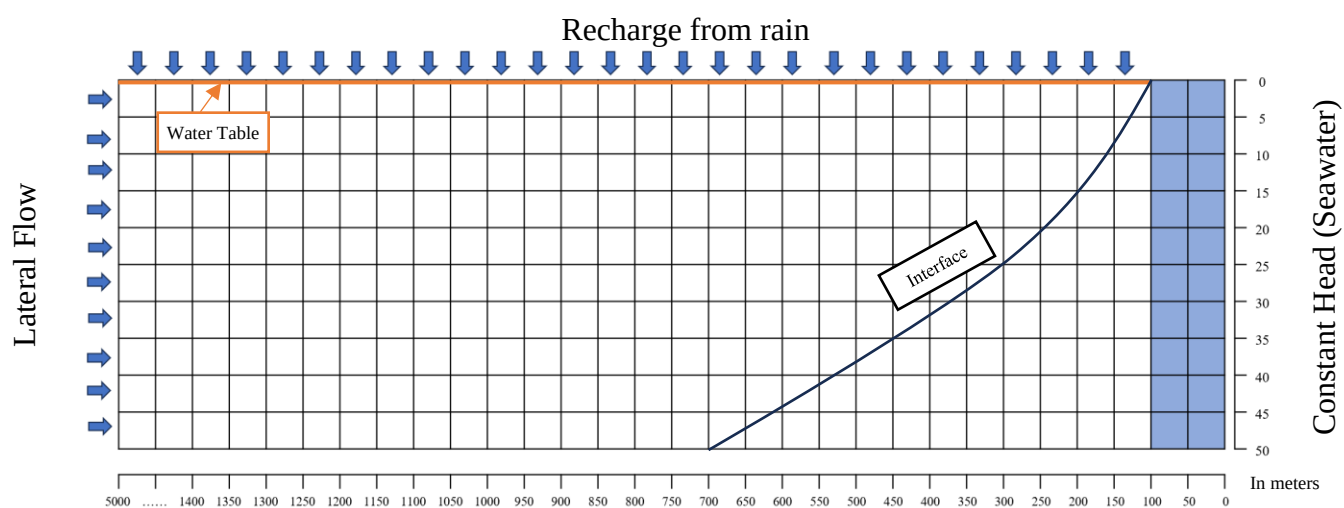


Figure 6. Sketch of Conceptual Model in Modeling Software.

4.3. Numerical Model

4.3.1. Model Selection

The computer codes utilized in this research include a modular finite-difference flow model (MODFLOW) [68], with mass transport modeling software MT3DMS [69]. In addition, SEAWAT, which is the variable-density groundwater flow and transport model, was used [70]. MT3DMS uses the output data from MODFLOW including groundwater levels, flow line directions, and water velocities, for the simulation of solute transport [71]. SEAWAT, which integrates MODFLOW and MT3DMS, is used to model the DDFM flow and solute transport.

4.3.2. Governing Equation

The mathematical equation that represents the movement of groundwater flow through porous media in 3D is [72]:

$$\frac{\partial}{\partial x} \left(K_x h \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y h \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z h \frac{\partial h}{\partial z} \right) - W = S_s \frac{\partial h}{\partial t} \quad (4.1)$$

Where in x, y, z coordinates, the values of hydraulic conductivity are K_x, K_y , and K_z , respectively [L/T]. The head is denoted by h [L], and the flux is denoted by W [L³/T]. S_s denotes the specific storage with a dimensionless unit, and t is time [T].

For the transport of contaminants in groundwater, the 3D mathematical equation is given by [88]:

$$\frac{\partial}{\partial x_i} \left(D_i \frac{\partial C}{\partial x_i} \right) - \frac{\partial}{\partial x_i} (v_i C) \pm \frac{q_s}{\theta} C_s = \frac{\partial C}{\partial t} \quad (4.2)$$

where D_i is the dispersion coefficient [L²/T] along the relevant coordinate axis, and x_i is the distance [L]. In addition, C stands for the contaminant (dissolved solute) concentration in the groundwater [M/L³], C_s for the source or sink flux concentration [M/L³], v_i for the groundwater

flow velocity [L/T], q_s for the flow rate per unit volume of sources (positive) or sinks (negative) [1/T], θ for the dimensionless porosity, and t for time [T].

It is considered that the density of the fluid is primarily a function of the solute concentration when simulating seawater intrusion through the SEAWAT code. While the effects of heat and pressure on the fluid density are neglected [73]. The following linear equation of state, which the SEAWAT uses to translate solute concentration into fluid density, can be expressed as follows [74]:

$$\rho = \rho_f + \frac{\partial \rho}{\partial C} C \quad (4.3)$$

Where $\frac{\partial \rho}{\partial C}$ denotes the slope of the above equation, and its value shall be identified manually by the user. The symbol C is salt concentration [M/L³], and ρ_f is density of freshwater [M/L³].

4.3.3. SEAWAT Model Development

The SEAWAT model was used to simulate seawater intrusion in the coastal aquifers of the Eastern Province of Saudi Arabia. The model used current condition data to predict future seawater intrusion under different climate change scenarios. Simulation details will be mentioned in the following sections.

4.3.3.1. Simulation Period

The simulation period in this study extended up to the year 2100 as shown in Table 2. The first period is a steady state for 1 year (365 days), and the results from the steady state period are used as the initial condition for the transient simulation. The main simulation period is transient and lasts for 123 years (assuming it begins from the year 1900 to 2023) which shows the development effects in the area. In this period, groundwater pumping is introduced, with changes in recharge

rates and sea level rise. The last period represents the three climate scenarios, where the sea level and precipitation change differently in each scenario.

Table 2. Simulation Periods of the Model.

Period	Start (days)	Length (days)	Number of Time Step	Steady State
1	0.0	365.0	1	1
2	365.0	3649635.0	1000	0
3	3650000.0	44895.0	50	0
4	3694895.0	28105.0	50	0
End	3723000.0			

4.3.3.2. Boundary Conditions

Based on the conceptual model shown in Figure 6, the recharge occurs on the top of the aquifer. The sea boundary on the right is considered as a time-variant specified head. The sea level was assumed to vary linearly with time-based on climate change models. The general head boundary is assigned to the left boundary to represent the lateral flow to the aquifer.

4.3.3.3. Model Grid

The grid used is cell-centered and is 5000 m in length, 50 m in depth, and 50 m in width. The cell resolution is 100 m in length, 5 m in depth, and 50 m in width. Table 3 shows the grid settings used in detail.

Table 3. Grid Settings.

Item	Value	Unit
Grid type:	Cell Centered	
X origin:	0	(m)
Y origin:	0	(m)
Z origin:	0	(m)
Length in X:	5000	(m)
Length in Y:	50	(m)
Length in Z:	50	(m)

4.3.3.4. Model Initial Conditions

The results of the steady state period were used as the initial condition for the transient models. For the transient solute model, the initial salt concentration assigned to the model is 42,000 mg/l, based on measured salinity in the Arabian Gulf [75].

4.3.3.5. Hydrogeological Parameters

Hydrogeological parameters for the design models have been assigned in Table (4):

Table 4. Hydrogeological Parameters Assigned to the Model.

Parameter Value	Value	Unit
Hydraulic conductivity [39]	2.592	m/d
Total porosity [76,77]	0.3	
Specific storage [39]	0.000011	m ⁻¹
Specific yield [39]	0.01	

4.3.3.6. Recharge & Sea Level Rise Parameters

Recharge

Analyzing historical rainfall in Saudi Arabia is complex due to the irregular and intense nature of precipitation in the region. Unlike temperature changes, rainfall patterns have been less consistent across the country. In recent decades, there has been a general decline in both annual and wet-season rainfall. However, certain areas in the eastern, northwestern, and southern regions have seen a slight increase in precipitation.

Table 5. AAP from 2010-2022 Compared to Long-Term AAP (1961-1991)

Variable (ml)	Years												
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Annual Average of Precipitation	81	62.8	57	88	63	71	96	68	127	96	86	63	99
Annual Average on Long-Term (1961-1991)	87.5												

Table (4) shows the increase in the average annual precipitation (AAP) from 2010 to 2020 compared to the long-term annual average from 1961 to 1991. The average precipitation reached almost 90 mm/year in the Eastern Province [78]. For the recharge rate of the study area, 5% of the current precipitation rate is used. This is equivalent to 4.5 mm/yr. [79,80]

Table 6. Recharge Rates for the Modeled Scenarios

Model Scenario	Precipitation mm/yr	Recharge mm/yr
Current Conditions (CC)	90	4.5
Scenario 1 (Min.)	96.3	4.815
Scenario 2 (Inter.)	102.6	5.13
Scenario 3 (Max.)	119.7	5.985

Sea Level Rise

In concordance with global trends, there is an observable rise in sea levels within the Red Sea and the Arabian Gulf. This phenomenon is predominantly ascribed to the processes of ice sheets and glacier melting, along with the thermal expansion of oceans due to their warming [81]. Notably,

the Red Sea exhibited an average annual sea level rise of 5.7 mm between 2006 and 2018, and 4.1 mm from 1993 to 2022. On the other hand, the Arabian Gulf had a yearly rise in sea level of 3.4 mm from 2006 to 2018 and 3.9 mm from 1993 to 2022 [81,82]. The Arabian Gulf's sea level increase closely resembles the global average, with an average rise of 4.0 mm considered a normal scenario [83].

4.4. Modeling Scenarios

To study climate change's impact on the aquifer, three scenarios are introduced. The first scenario "SC1" considers the low impact, thus minimal increase in recharge rates and sea level. Scenario 2 "SC2" considers the impact of increasing recharge rates with further sea level rise. The third scenario "SC3" considers the impact of maximum sea level rise, with a high recharge rate.

4.5. Summary of Model Limitations

To measure the effective climate change factors that affect the seawater intrusion phenomenon, a set of assumptions have been stated to limit the contribution of other factors to the results. These assumptions are summarized as follows:

- The current pumping rate is constant and will remain the same in climate change models.
- The lateral flow rate is constant.
- The current sea level is zero.
- The sea level was assumed to vary linearly with time-based on climate change models.
- Steady-state conditions are assumed for the first period due to the relatively constant annual recharge and pumping rates observed in this region. Results of the steady state are used as initial conditions for the transient periods of the model.
- The aquifer is considered homogenous with a horizontal to vertical anisotropy factor of 1:10.

4.6. Model Input Data

Hydrogeological and metrological parameters have been inserted into the model file, Table (6) summarizes input data for the current condition and each projected scenario. The Variable Density Flow (VDF) package of SEAWAT relied on the slope of density over-concentration (DRHODC) ($\partial\rho/\partial C$ in Equation (4.2)). It is a critical variable to establish the relationship between density and concentration. A computed slope of 0.583 was applied in the package based on the assumptions of seawater and freshwater concentrations of 42.0 and 0.0 g/L, respectively, and seawater and freshwater densities of 1025 and 1000 kg/m³, respectively.

Table 7. Summary of Model Scenario Input Data

Parameter Value	Value in CC	Value in SC1	Value in SC2	Value in SC3	Unit
Hydraulic conductivity	2.592	2.592	2.592	2.592	m/d
Total porosity	0.30	0.30	0.30	0.30	
Specific storage	0.000011	0.000011	0.000011	0.000011	m ⁻¹
Specific yield	0.01	0.01	0.01	0.01	
Sea level rise [97]	0.3	0.58	0.7	0.91	m
Recharge rate [97]	0.00001233	0.00001319	0.00001405	0.00001640	m/d

CHAPTER 5: RESULTS AND DISCUSSION

Simulation results include flow (Heads) and salt transport. The flow results are categorized into two sections: early flow model and historic simulation, which will be up to the year 1900, and flow model in the development era, from the year 1900 to 2023. The salt transport results will be represented in three sections: up to the year 1900 (flushing the saltwater by rainfall recharge), the development phase (1900 to 2023), and future scenarios (2023 to 2100).

5.1. Flow Results

5.1.1. Early Flow Model

Due to the lack of data on the saltwater-freshwater interface in the study area, a long transient simulation period that lasts for 10,000 years was performed. Fig. 7 shows the washing salts towards the sea during the 10,000 years of simulation period, which results in the natural conditions before development.

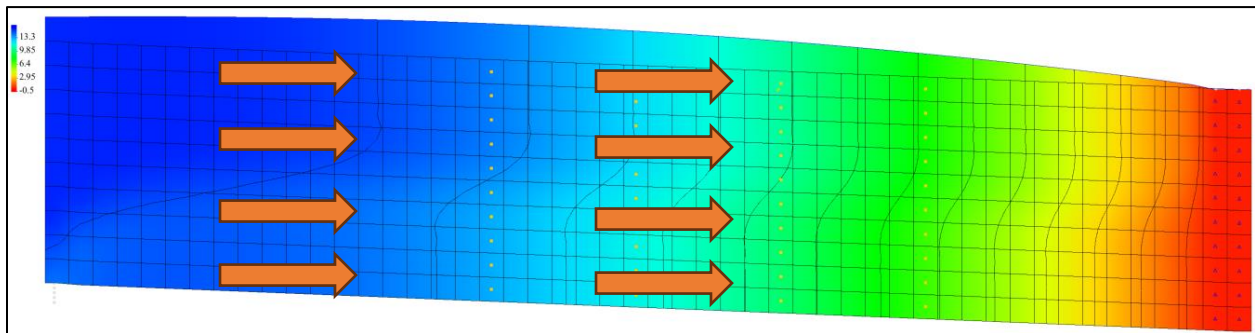


Figure 7. Flow Directions in the Early Flow Model (Orange Arrow)

5.1.2. Flow Model in the Development Era

In this period (1900 – 2023), groundwater is included into the model to represent the beginning of development. As a result of pumping, the interface moves upward due to groundwater extraction as shown in Fig. 8.

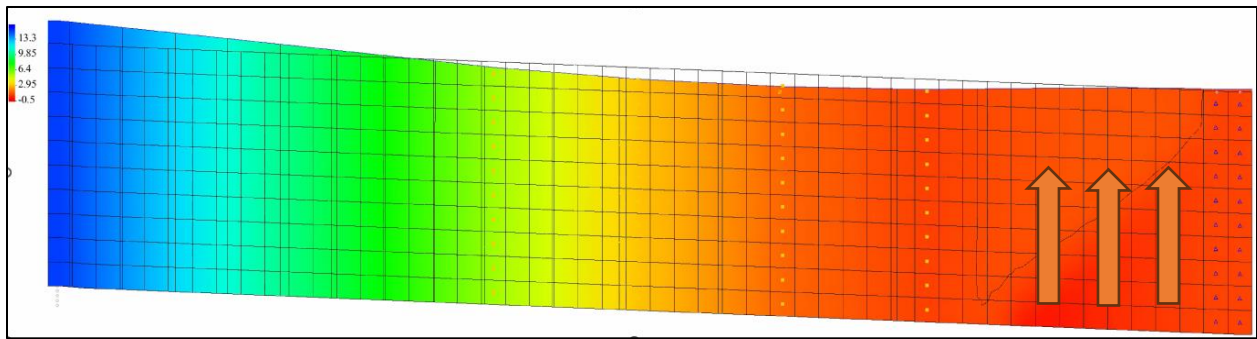


Figure 8. Upward Movement of the Interface Due to Groundwater Extraction (Orange Arrow)

5.2. Salt Transport Results

5.2.1. Early Salt Transport Model

The early salt transport model represents the historical period up to the year 1900, where the salts have been washed from the land towards the current shoreline (Figure 9,10), due to recharge and lateral flow.

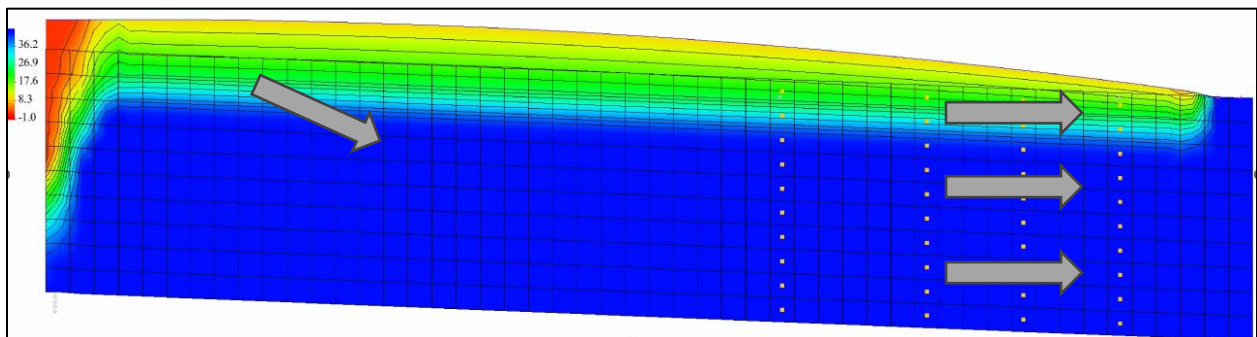


Figure 9. Direction of Salt Transport Downwards & Towards Shoreline (Grey Arrows)

5.2.2. Salt Transport Model in the Development Era

Since the development began (i.e. groundwater extraction), the freshwater-saltwater interface moved further inland. In Fig. 10, the interface is illustrated to be exactly on the sea shoreline.

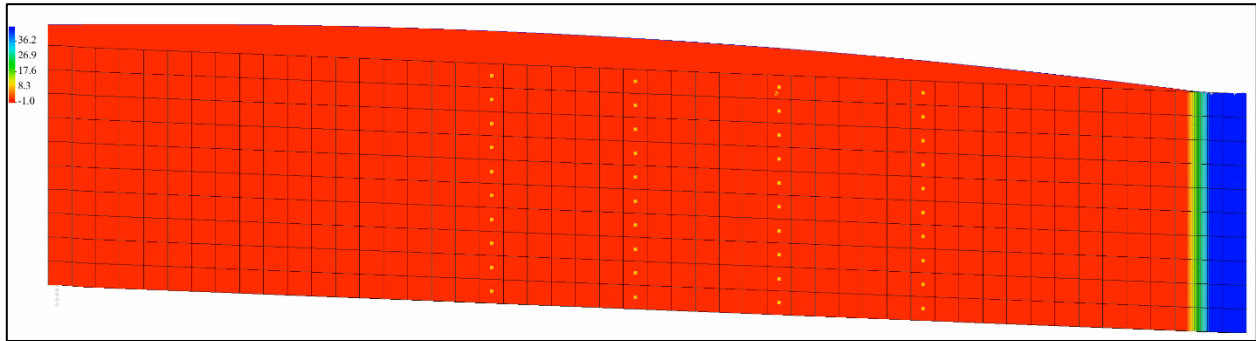


Figure 10. The Interface is Set Exactly on the Shoreline (year 1900)

The interface movement was affected by the recharge, sea level rise, and groundwater extraction in the area. These factors push the interface further inland (Fig. 11) resulting in contaminating and salinizing of the fresh groundwater.

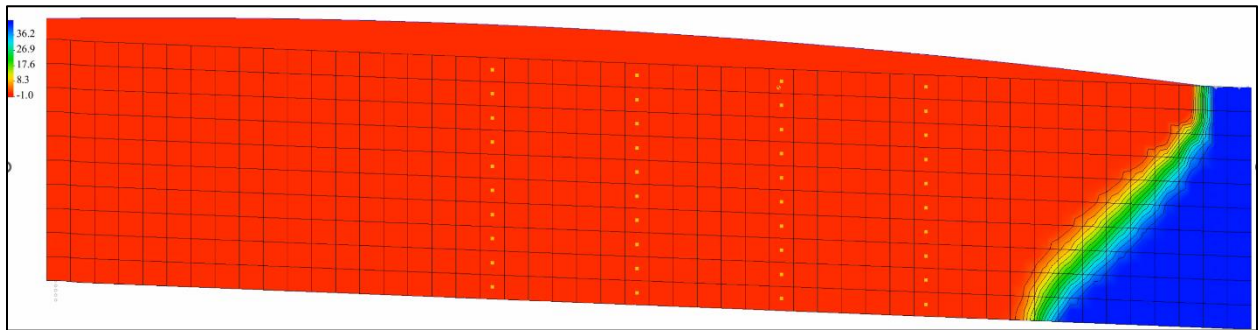


Figure 11. Current Condition of the Interface After Development (year 2023)

5.2.3. Results of Climate Model Scenarios

Minimal Effects Scenario

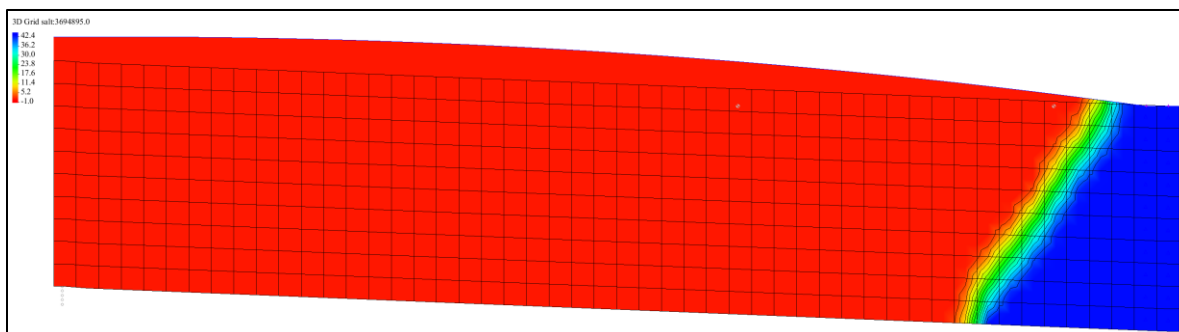
In the first scenario “SC1”, the results indicate that the encroachment of salt water may reach 1,400 meters horizontally from the sea towards the aquifer. This indicates a horizontal increase in the extent of saltwater reaching the bottom bed of the aquifer, where the increase in distance is 27% more compared to the current situation, where salt water has reached a range of 980 meters. Figure 12 shows the encroachment extent during the years 2023 to 2100.

Intermediate Effects Scenario

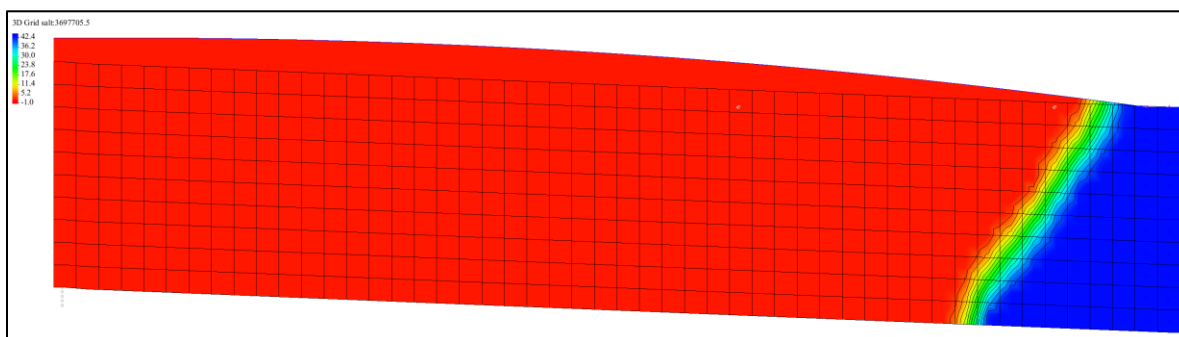
In the second scenario “SC2”, the results indicate that the encroachment of salt water may reach 1,450 meters horizontally from the sea towards the aquifer. This indicates a horizontal increase in the extent of saltwater reaching the bottom bed of the aquifer, where the increase in distance is 32% more compared to the current situation, where salt water has reached a range of 980 meters. Figure 13 shows the encroachment extent during the years 2023 to 2100.

Maximal Effects Scenario

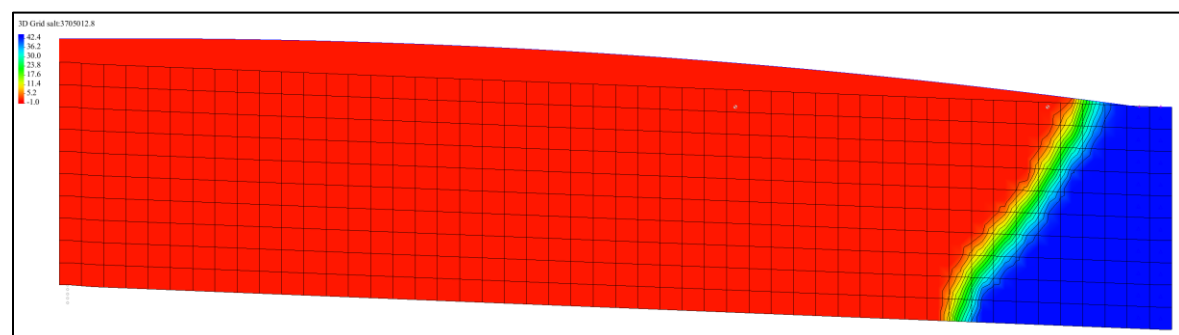
In the second scenario “SC2”, the results indicate that the encroachment of salt water may reach 1,500 meters horizontally from the sea towards the aquifer. This indicates a horizontal increase in the extent of saltwater reaching the bottom bed of the aquifer, where the increase in distance is 37% more compared to the current situation, where salt water has reached a range of 980 meters. Figure 14 shows the encroachment extent during the years 2023 to 2100.



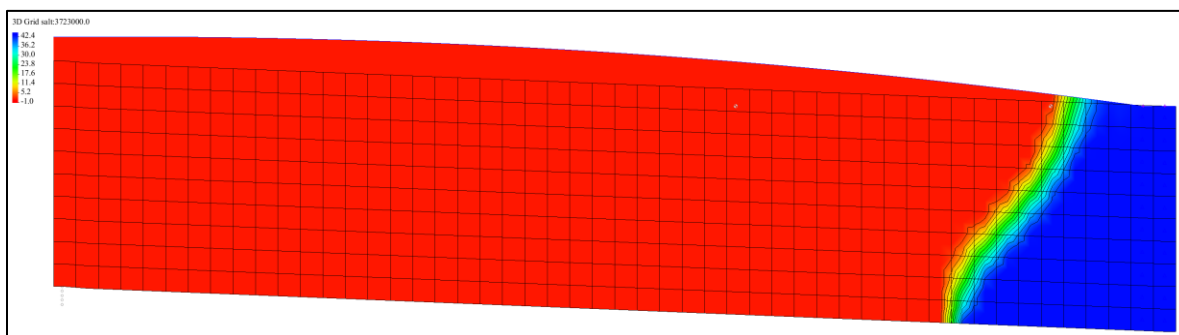
CC (2023)



SC1 (2030)

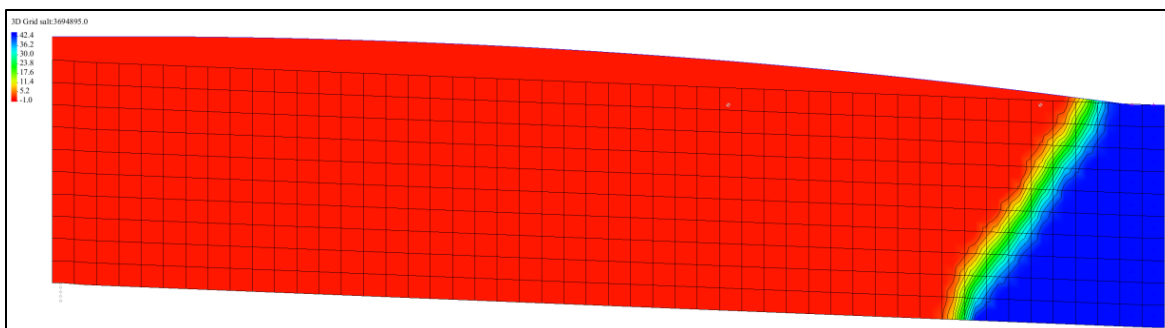


SC1 (2050)

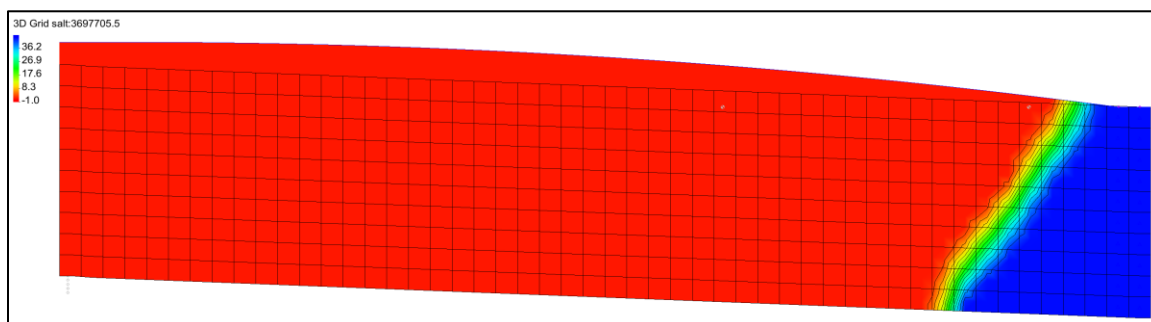


SC1 (2100)

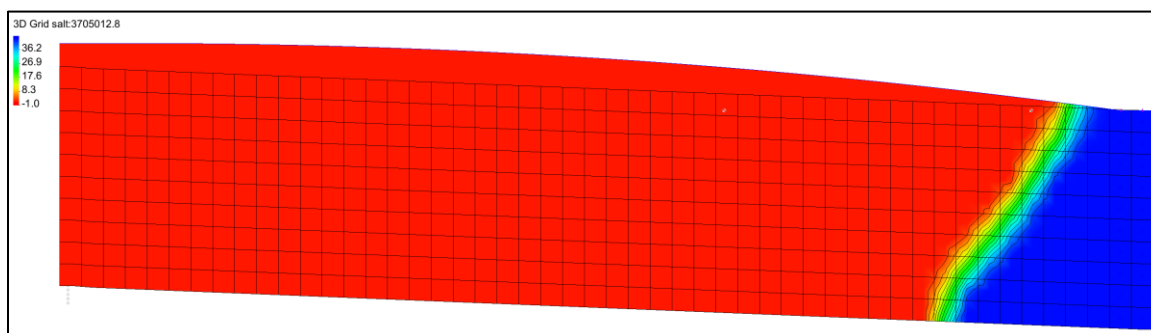
Figure 12. Saltwater Encroachment of "Min" Climate Change Scenario



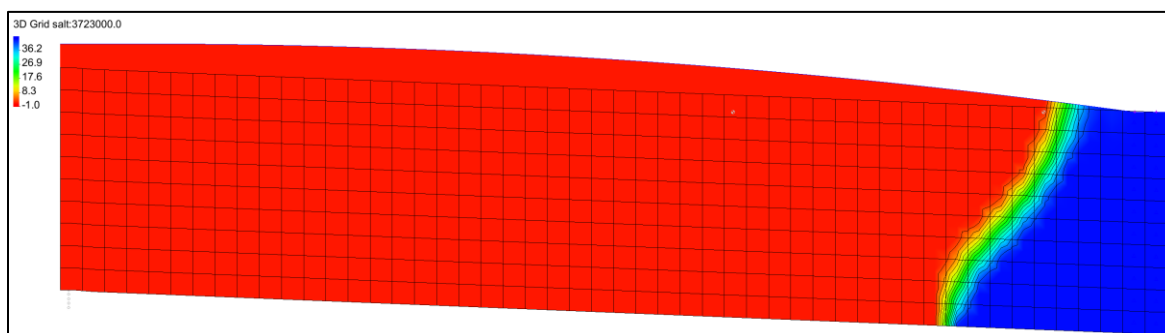
CC (2023)



SC2 (2030)

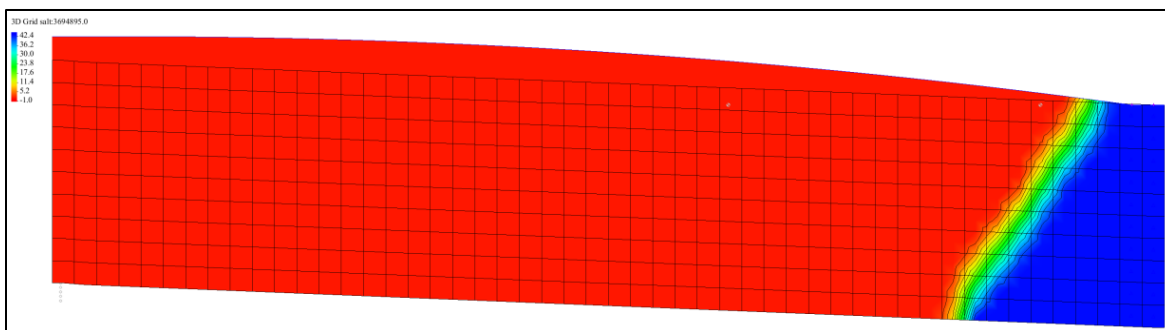


SC2 (2050)

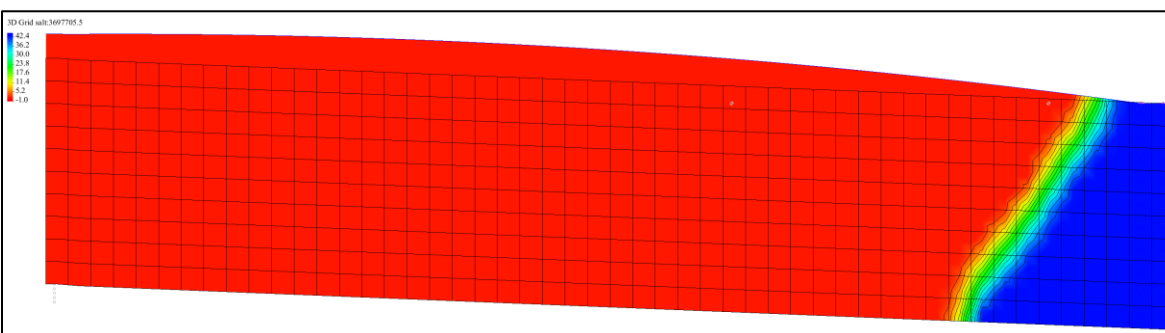


SC2 (2100)

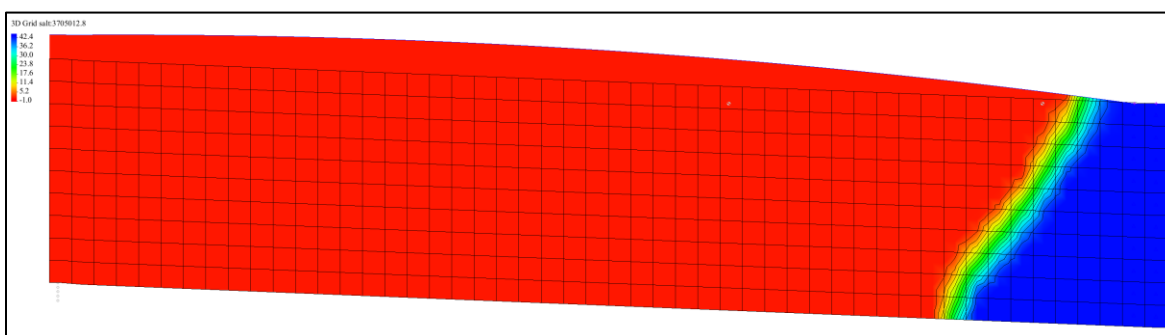
Figure 13. Saltwater Encroachment of "Intermediate" Climate Change Scenario



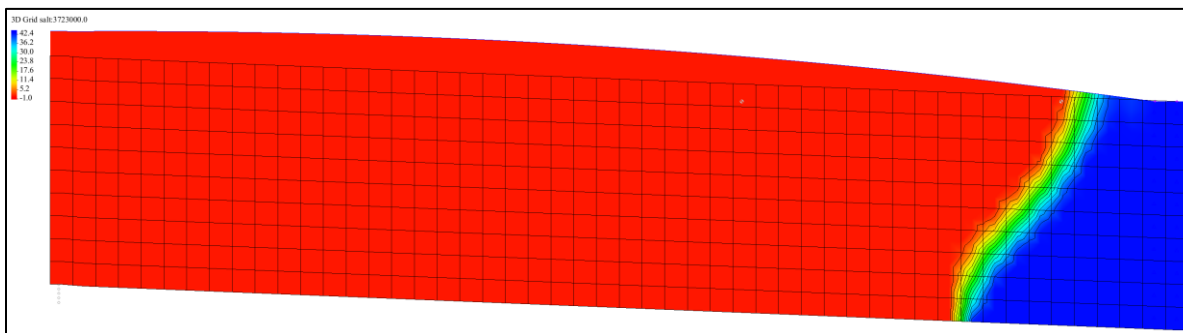
CC (2023)



SC3 (2030)



SC3 (2050)



SC3 (2100)

Figure 14. Saltwater Encroachment of "Max" Climate Change Scenario.

5.3. Climate Models Discussion

The input data for the model scenarios have been summarized in Appendix A. Results of modeled scenarios have shown different deviations of inland salt encroachment for each scenario and the distances are summarized in Table 9, with each green shaded cell indicating 100 meters inland.

Table 8. Comparison of Saltwater Distance Inland

Cell Location				Salt Data mg/L			
ID	K	I	J	Current Condition	(SC1)	(SC2)	(SC3)
485	10	1	35	1.87E-19	6.51E-16	2.34E-11	3.20E-11
486	10	1	36	1.88E-19	1.84E-10	6.62E-06	1.44E-05
487	10	1	37	4.49E-20	4.1E-05	2.148961	12.45572
488	10	1	38	3.08E-15	3.146573	19.51487	36.80821
489	10	1	39	4.18E-10	21.34899	38.52764	41.99568
490	10	1	40	4.17E-05	40.01716	41.99957	42.00445
491	10	1	41	3.287087	42.00181	42.00406	42.00158
492	10	1	42	23.98246	42.0037	42.00064	41.99977
493	10	1	43	41.79976	42.00025	41.99978	41.99973
494	10	1	44	42.00288	41.99983	41.99977	41.99977
495	10	1	45	42.00031	41.99983	41.99987	41.99991
496	10	1	46	41.99978	41.99993	41.99998	42
497	10	1	47	41.99979	42	42	42
498	10	1	48	41.99997	42	42	42
499	10	1	49	42	42	42	42
500	10	1	50	42	42	42	42
Horizontal Inland Distance of Saltwater into aquifer base (m)				980	1400	1450	1500
Percent of Change Compared to the CC Model				-	27	32	36

To compare all results of the climate model scenarios, Figure 15 illustrates how salt is encroaching on coastal lands. In the figure, the horizontal extent of salts from the shoreline is represented in

lines; Considering the blue represents the current condition (i.e. year 2023), while the orange, grey, and yellow lines represent “SC1”, “SC2” and “SC3” respectively.

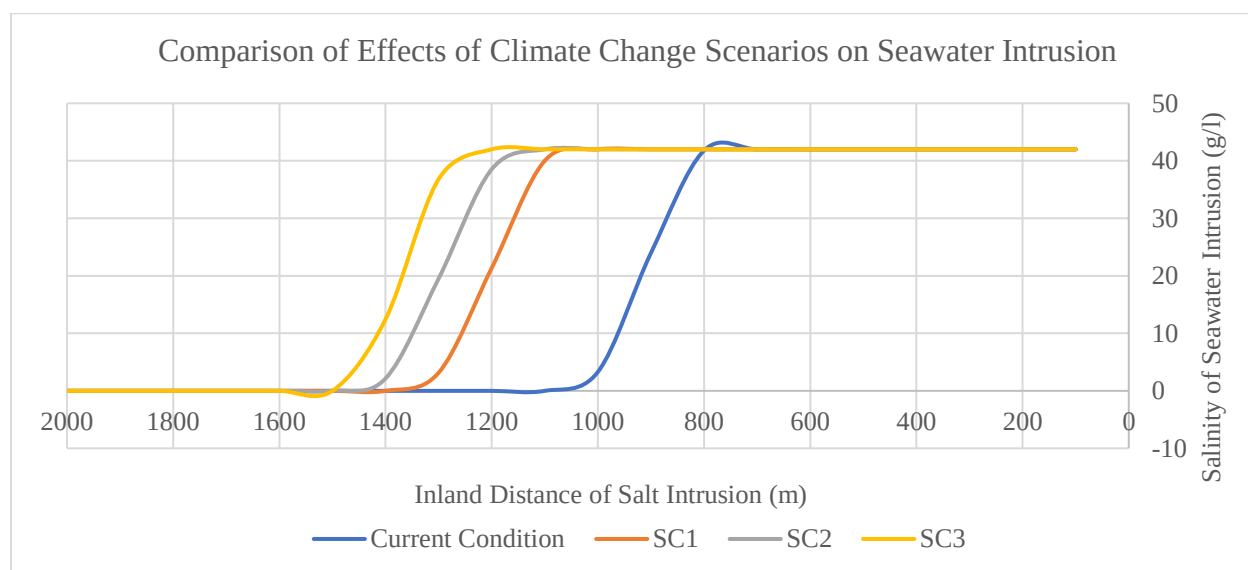


Figure 15. Comparison Chart of Effects of Climate Change Scenarios on Seawater Intrusion

Figure 16 illustrates how salt is encroaching into coastal lands with a 27% increase in horizontal distance for the SC1 scenario compared to CC, and for other scenarios, the percent of increment reached 32% and 36% for SC2 and SC3, respectively, compared to current conditions.

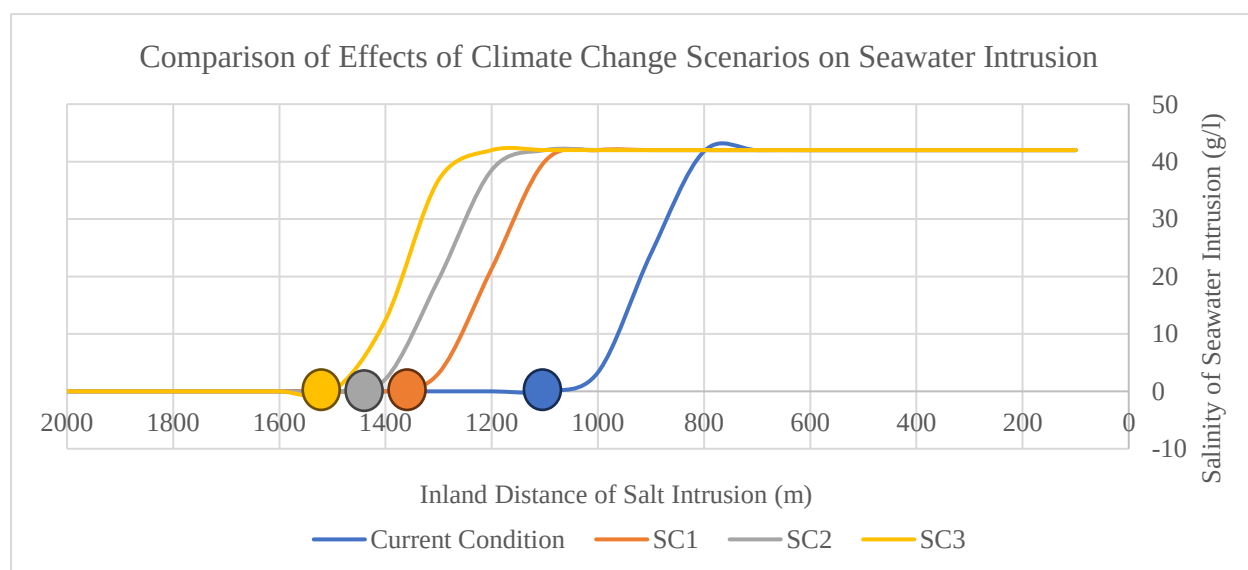


Figure 16. Comparison between Climate Change Model Scenarios on the Extent of Salinity of the Aquifer Bed Resulted from Seawater Intrusion

To present the impacted underground area of seawater salinity, Figure 17 shows the impacted area of current condition (blue-colored).

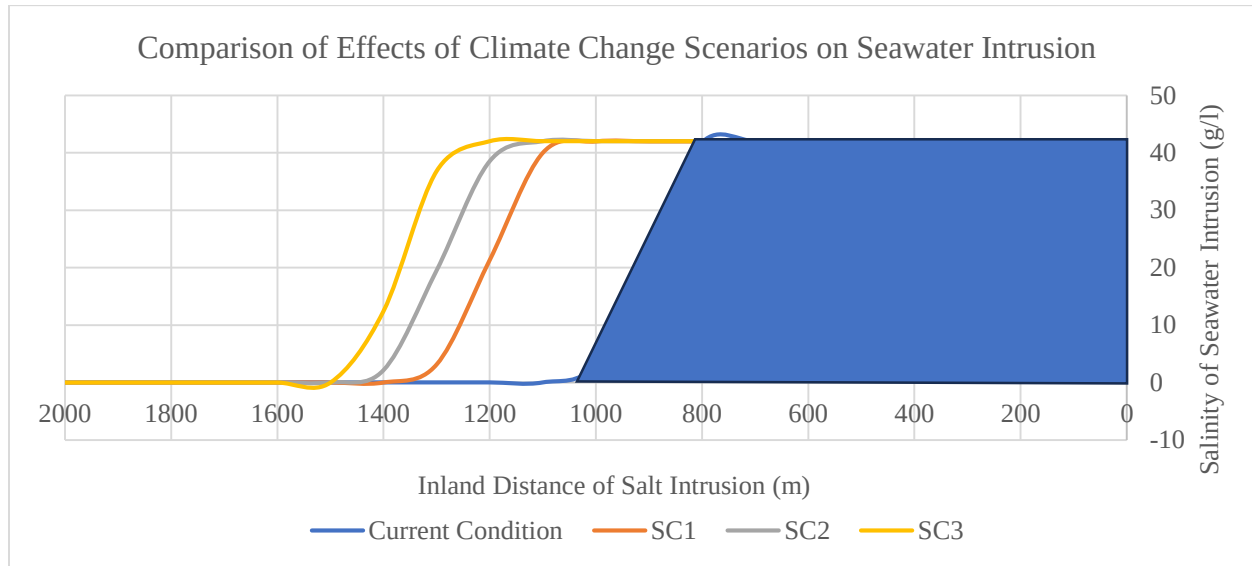


Figure 17. Impacted Underground Area of Seawater Salinity for Current Condition Scenario.

Comparing the effect of climate scenarios on the impacted underground area of seawater salinity, Fig. 18 represents the increment percentage of salinized area per scenario. In Fig. 18, orange, grey, and yellow areas represent “SC1”, “SC2” and “SC3” scenarios. These colored areas represent the impact salinized area per unit width of the aquifer. The first scenario shows 33.45% increase in area compared to the current condition (blue-dashed area), while “SC2” and “SC3” shows 43.83%, and 52.38% increment in the area compared to the current condition, respectively.

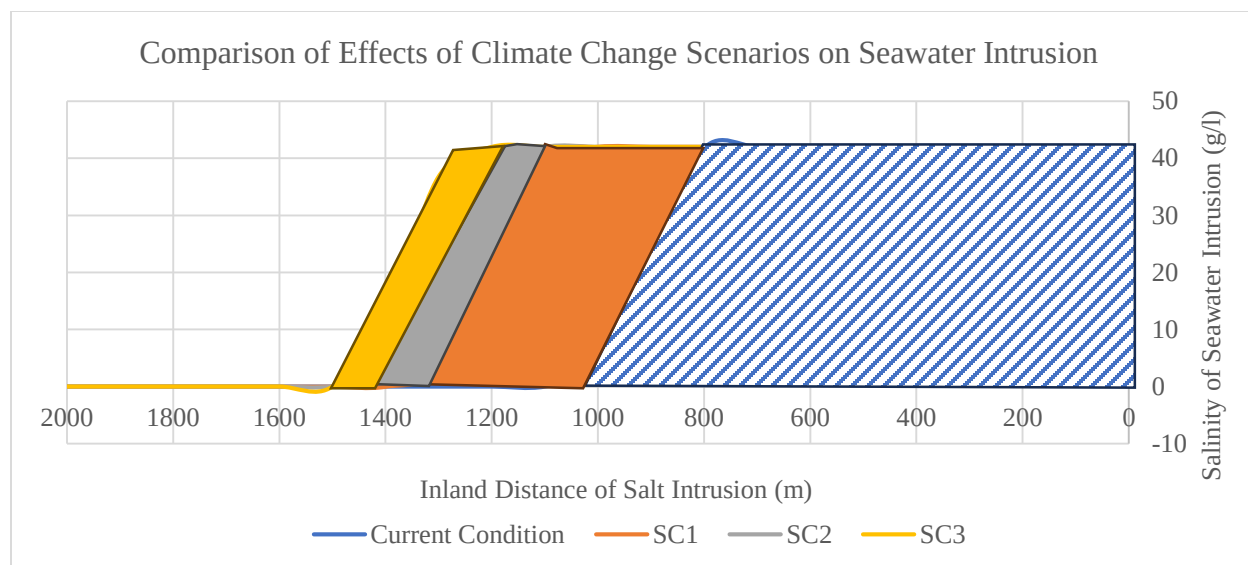


Figure 18. Comparison of Salinized Underground Area Between Climate Change Scenarios

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

Coastal aquifers are important, serving as a crucial resource for sustaining ecosystems, and a primary source of water for over 2 billion people worldwide [3]. The Eastern Province of Saudi Arabia encounters distinctive challenges arising from the interaction of climate change and coastal aquifers, emphasizing the importance of understanding these processes. Due to rising sea levels and changing rainfall patterns, the coastal aquifers in the region are vulnerable to infiltration of seawater inland.

Climate change models in conjunction with the seawater intrusion models provide valuable insights into the dynamics of seawater intrusion in the Eastern Province of Saudi Arabia. The study demonstrated that the anticipated changes in climate, including variations in sea level rise and precipitation patterns, vary in influencing groundwater-surface water interactions and subsequent seawater intrusion.

The study findings clarify that climate change amplifies seawater intrusion in the Eastern Province of Saudi Arabia through a combination of factors, including sea level rise, reduced groundwater recharge, and groundwater overexploitation. Seawater intrusion modeling concludes that “SC1” scenario reached a 27% more in horizontal intrusion compared to current conditions. But the results of SC2 and SC3 show further encroachment of saltwater inland, where salt water have reached 32% and 37%, respectively.

This extent of saltwater encroachment may reach 1,500 meters inland along the coastal line of the Eastern Province and could have several environmental consequences in the area. It may increase soil salinity, impacting crop growth. This intrusion can contaminate groundwater sources, crucial

for both drinking water and agriculture, leading to potential health hazards. Additionally, corrosive saltwater can damage infrastructure, especially coastal commercial and industrial cities like Al-Jubail, necessitating increased maintenance costs and posing safety risks. Human settlements within the affected zone, like Al-Jubail City Center, might experience degradation of living conditions, potentially forcing relocations. Thus, mitigation strategies should be implemented, including building seawalls, managing groundwater effectively, and developing salt-tolerant crops to adapt to these challenges.

6.2. Recommendations

Engineering-based recommendations could include injection of fresh water in the aquifer or reduce the extraction of groundwater. Both solutions aim to push back the saltwater-fresh water interface towards the sea shoreline. These solutions have been tested in the following sections.

It is important to understand the importance of reducing groundwater extraction for sustainable water management. This can be achieved through the implementation of management effective methods by the relevant authorities, such as promoting water conservation, optimizing irrigation practices, and investing in alternative water sources. These steps are crucial in ensuring the long-term sustainability of water resources.

For a practical proposed solution from this study findings, Injection wells are used as follows:

- S1: 4th Well replaced as a source of 1 m³/d per cell, i.e. injection of water.
- S2: 4th Well as a Source (0.5 m³/d per cell)

The effected saline-area of “SC3” has changed per the proposed solutions of injection wells. For S2 case, the effected saline-area in the aquifers has reduced and becomes close to the current condition with small increase of 3.7% only. While for the S1 case, the injected fresh water has

pushed back the saltwater-freshwater interface towards the sea shoreline and reduced the current condition of saline-area by 12.64%. Figure 20 illustrates the effectiveness of S1 and S2 proposed solution of injection wells compared to the current condition.

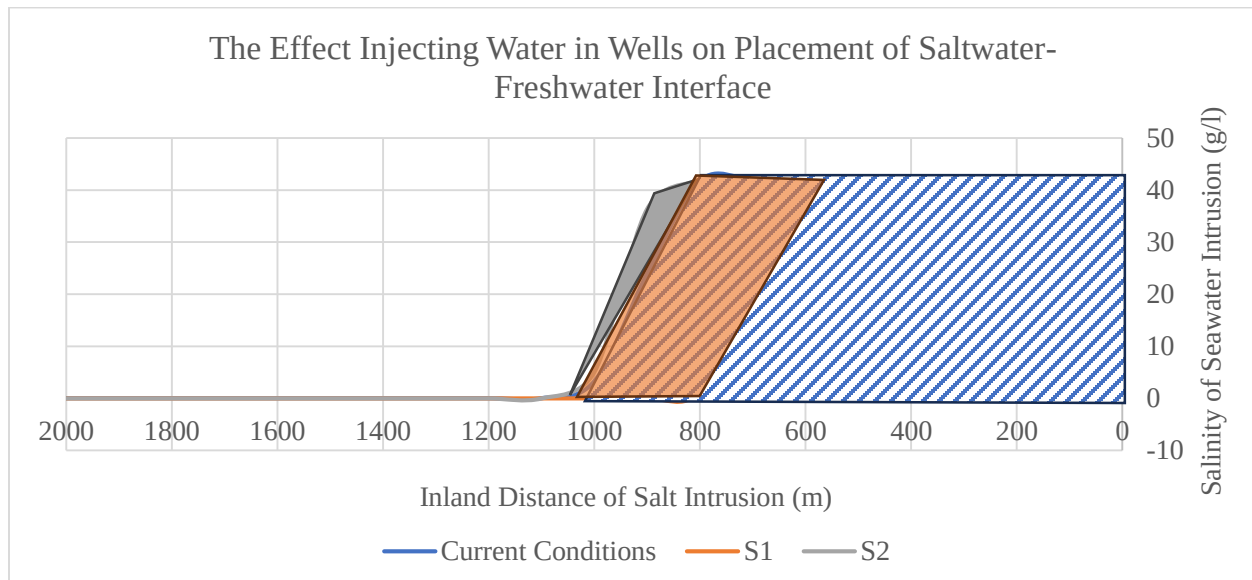


Figure 19. The Effect Of Injecting Water in Wells on Placement of Saltwater-Freshwater Interface

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Appendices

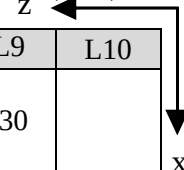
Appendix A: Input Data for Modeling Software

Table 9. Input hydrogeological data

Variable	Porosity	Horizontal Hydraulic Conductivity [m/d]	Vertical Anisotropy (Kh/Kv)	Horizontal Anisotropy	Specific Storage [1/m]	Specific Yield
Values in all cells and layers	0.3	0.3	10	1	0.000011	0.01

Table 10. Values of starting heads and top elevations from layer 1 (L1) to layer 10 (L10)

Variable	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10
Starting Heads = Top Elevation	10	5	0	-5	-10	-15	-20	-25	-30	



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- Certificate of non-credit Specialization on Six Sigma - Green Belt, from University of Georgia
- Introduction to Cybersecurity form Cisco