UNIVERSITI PUTRA MALAYSIA

USING DENSITY DEPENDENT APPROACH FOR SIMULATION AND CONTROL OF SEAWATER INTRUSION INTO COASTAL AQUIFERS

MOHAMMED SALEH SAAD NUSARI

FK 2014 151

**USING DENSITY DEPENDENT APPROACH FOR SIMULATION AND
CONTROL OF SEAWATER INTRUSION INTO COASTAL AQUIFERS**

By

MOHAMMED SALEH SAAD NUSARI

DEDICATION

This work is dedicated to my dear parents, wife, children, brothers and sisters; their patience and support has been my motivation and inspiration.

Abstract of the thesis submitted to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

USING DENSITY DEPENDENT APPROACH FOR SIMULATION AND CONTROL OF SEAWATER INTRUSION INTO COASTAL AQUIFERS

By

MOHAMMED SALEH SAAD NUSARI

September 2014

Chairman: **Professor Mohd Amin Mohd Soom, Ph.D., P.Eng., FIEM.**
Faculty: **Engineering**

Seawater intrusion threatens freshwater resources in coastal communities worldwide. The actual seawater intrusion mechanism is still not well understood. In addition availability of benchmark problems used for testing numerical seawater intrusion model is limited, and agreeable solutions on existing benchmark test problems are still subject to debate and remained unresolved. Laboratory studies that can promote better understanding of seawater intrusion mechanism based on the density dependent approach and verify numerical density dependent models also have made little progress. Hence there is a need to experimentally and numerically simulate seawater intrusion based on the density dependent approach to better understand the movement and mixing of freshwater and saltwater and produce experimental datasets under steady-state and transient conditions. A controlled large-scale physical model aquifer was designed and constructed for this study. This tank model was used to simulate the advancement of seawater intrusion into coastal aquifers based on the density dependent approach under steady-state and transient conditions. Numerical model SEAWAT-2000 was then employed to reproduce experimental datasets. Three tests were conducted to analyze the applicability of the seawater intrusion experimental datasets developed in this study as alternative benchmark problems. Physical and numerical models were also used to assess the effectiveness of aquifer recharging by injecting freshwater and discharging of brackish water from the mixing zone. The 3D density dependent numerical model based on SEAWAT-2000 code was developed to determine the current condition and predict future situations of seawater intrusion into the semi-confined aquifer in the lowlands of Langat Basin, Malaysia that served as a case study. After the model was calibrated by using data from 2010, it was used to predict future extent of seawater intrusion up to 2045, assuming that the current condition of Langat Basin remains unchanged.

The experimental setup of the aquifer physical model provides a novel technique for simulating seawater intrusion based on density dependent approach. This in turn gives a better understanding of the actual mechanism of movement and mixing of fresh and saline water and the factors influencing these processes. This work has provided a set of new benchmark datasets for testing saltwater intrusion numerical models. This will greatly benefit the density dependent flow and solute transport modeling community through the provision of accurate solution to the saltwater

intrusion problem. This can then be used as an alternative benchmarking solution. The results demonstrated the development, position, pattern or shape of seawater intrusion wedge induced by changes in the transmitted freshwater inflow rate through the aquifer physical model. The growth and decay of the mixing zone showed a narrow mixing zone occurred when freshwater inflow rate was high. However, the mixing zone was significantly widened with decreasing freshwater inflow rate. Multiple datasets were generated from the collected data on salt concentration distribution in the aquifer model and the measurement of transmitted freshwater inflow through the aquifer physical model. These experimental datasets were compared with the numerical results generated from the SEAWAT-2000 simulation. Good agreement was found between the results. The results of the applicability analysis of the experimental datasets as alternative benchmark data showed that the transient seawater intrusion experimental data can be used to validate the accuracy of coupled-density dependent models. To control the advances of seawater intrusion, discharging brackish water from the saltwater zone has a considerable effect on the retardation of seawater intrusion, but it is less effective than recharging. Recharging by multiple injection wells as a control method and discharging saline water by multiple discharge wells are more effective than recharging by single injection wells and discharging by single discharge wells in reducing the inland movement of seawater intrusion wedge. Hence freshwater injection is more effective than discharging saline water. The developed model of the Langat basin aquifer has provided a clear picture of the current and future situation of seawater intrusion into the aquifer. Assessment of the intrusion shows that the aquifer will be significantly influenced by seawater intrusion for the next 35 years. This model contributes to improve understanding of the dynamic process of seawater intrusion in the area being studied. This would aid in choosing the most suitable control method in order to prevent the advancement of seawater into the main aquifer. The outcomes of this model can be considered as a foundation to protect water resources in other coastal aquifers under similar hydrogeological conditions.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGGUNAAN PENDEKATAN KEBERGANTUNGAN KETUMPATAN UNTUK SIMULASI DAN PENGAWALAN PENCEROBOHAN AIR LAUT KE DALAM AKUIFER PANTAI

Oleh

MOHAMMED SALEH SAAD NUSARI

September 2014

Pengerusi: Professor Mohd Amin Mohd Soom, Ph.D., P.Eng., FIEM.
Fakulti: Kejuruteraan

Pencerobohan air laut menggugat sumber air tawar terhadap komuniti pantai di seluruh dunia. Mekanisme sebenar pencerobohan air laut belum difaham sepenuhnya. Malah, ketersediaan penanda aras permasalahan yang diguna untuk menguji model berangka pencerobohan air laut adalah terhad dan penyelesaian yang boleh disetujui bagi pengujian penanda aras permasalahan yang sedia ada masih tertakluk kepada debat dan belum selesai. Kajian makmal yang boleh membantu kefahaman yang lebih baik terhadap mekanisme pencerobohan air laut yang berasaskan kaedah kebergantungan padat dan sedikit memajukan pengesahkan model berangka kebergantungan padat. Oleh itu, simulasi percubaan dan berangka adalah amat perlu bagi pencerobohan air laut yang berasaskan kaedah kebergantungan padat untuk lebih memahami pergerakan dan percamuran antara air tawar dan air masin dan juga menghasilkan set data percubaan dibawah keadaan mantap dan keadaan fana. Satu fizikal model akuifer yang bersekalar besar yang terkawal telah berjaya direkabentuk dan dibangunkan bagi kajian ini. Model tangki ini telah diguna bagi simulasi pergerakan pencerobohan air laut ke akuifer pantai berasaskan kaedah kebergantungan padat dibawah keadaan mantap dan keadaan fana. Model berangka SEAWAT-2000 telah diguna untuk menghasilkan set data percubaan. Kajian ini telah dijalankan untuk menganalisis kesesuaian set data percubaan pencerobohan air laut yang telah dibangunkan dari kajian ini sebagai penanda aras permasalahan. Model fizikal dan berangka turut digunakan bagi penilaian keberkesanan caj akuifer dengan cara suntikan air tawar dan pelepasan air payau dari zon campuran. Model berangka jenis kebergantungan ketumpatan dalam bentuk 3D yang berasaskan kod SEAWAT-2000 telah dibangunkan bagi penentuan keadaan semasa dan meanggarkan situasi masa depan pencerobohan air laut ke akuifer separa terkurung di tanah rendah kawasan tadahan Langat, Malaysia yang merupakan kawasan kajian kes ini. Setelah model ini ditentukurkan dengan penggunaan data dari tahun 2010, ia telah digunakan bagi meanggarkan pencerobohan air laut pada masa akan datang sehingga 2045 dengan tanggapan bahawa kondisi semasa bagi kawasan tadahan Langat tidak berubah.

Persediaan percubaan model akuifer fizikal memberi teknik yang novel bagi simulasi pencerobohan air laut berasaskan kaedah kebergantungan padat. Ini sebenarnya memberi kefahaman yang lebih baik terhadap mekanisme sebenar pergerakan dan

percampuran air tawar dan air masin dan juga factor yang mempengaruhi proses ini. Kajian ini memberi satu set data tanda aras baru bagi pengujian model berangka pencerobohan air masin. Ini akan memberi manfaat yang besar kepada komuniti pemodelan aliran kebergantungan padat dan pengankutan bahan larut melalui peruntukan penyelesaian yang tepat bagi masalah pencerobohan air laut. Ia kemudian boleh diguna sebagai penanda aras penyelesaian alternative. Keputusan menunjukan pembangunan, kedudukan, corak atau bentuk baji pencerobohan air laut didorongi oleh pertukaran kadar aliran masuk air tawar melalui model akuifer fizikal. Pertumbuhan dan kerosakan zon campuran semakin sempit apabila kadar aliran air tawar tinggi. Walaubagaimanapun, zon campuran menjadi lebar dengan ketara apabila kadar aliran masuk air tawar dikurangkan. Pelbagai set data telah dijana dari data pertaburan kepekatan garam yang terkumpul dari model akuifer dan pengukuran aliran air tawar yang menghantar melalui model akuifer fizikal. Set data percubaan ini telah dibandingkan dengan keputusan berangka yang dijana dari simulasi SEAWAT-2000. Persetujuan yang baik telah dijumpai dari kedua-dua keputusan. Keputusan analisa kesesuaian bagi set data percubaan sebagai data penanda aras alternatif menunjukan data percubaan pencerobohan air laut dalam keadaan fana boleh diguna untuk pengesahan ketepatan model gandingan kebergantungan padat. Untuk mengawal kemajuan pencerobohan air laut, pelepasan air payau dari zon air masin memberi kesan yang besar dalam melambatkan pencerobohan air laut tetapi ia kurang berkesan jika dibanding dengan cas air tawar. Pengecas air tawar dengan telaga suntikan yang banyak selaku satu kaedah kawalan dan pelepasan air masin oleh telaga pelepasan yang banyak adalah lebih berkesan dari pengecas oleh satu telaga suntikan dan pelepasan oleh satu telaga pelepasan bagi mengurangkan pergerakan baji pencerobohan air laut ke kawasan pendalaman. Oleh itu, suntikan air tawar adalah lebih berkesan dari pelepasan air masin. Model akuifer yang telah dibangunkan bagi kawasan tadahan Langat memberi gambaran yang jelas tentang situasi pencerobohan air laut kedalam akuifer pada masa sekarang dan akan datang. Penilaian pencerobohan menunjukan bahawa akuifer akan dipengaruhi secara ketara oleh pencerobohan air laut pada masa 35 tahun yang akan datang. Model ini menyumbang kefahaman yang lebih baik tentang proses dinamik pencerobohan air laut ke kawasan yang sedang dikaji ini. Ini mungkin membantu dalam pemilihan kaedah kawalan yang terbaik dalam pencegahan kemajuan air laut ke kawasan akuifer utama. Hasil model ini boleh ditanggap sebagai asas untuk mempertahankan sumber air bagi kawasan akuifer pantai lain yang kondisi hidrogeologikalnya sama.

ACKNOWLEDGEMENTS

I certify that a Thesis Examination Committee has met on 12 September 2014 to conduct the final examination of Mohammed Saleh Saad Nusari on his thesis entitled "Using Density Dependent Approach for Simulation and Control of Seawater Intrusion into Coastal Aquifers" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Lee Teang Shui, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Wan Nor Azmin bin Sulaiman, PhD
Professor
Faculty of Environmental Studies
Universiti Putra Malaysia
(Internal Examiner)

Badronnisa binti Yusuf, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Mohamed F. Dahab, PhD
Professor
University of Nebraska
United States
(External Examiner)

NORITAH OMAR, PhD
Associate Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 23 October 2014

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Mohd Amin Mohd Soom, PhD, P.Eng., FIEM
Professor, IR
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Thamer Ahmed Mohammed, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Abdul Halim Ghazali, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:
- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: _____ Date: _____

Name and Matric No.: Mohammed Saleh Saad Nusari, GS18453

Declaration by Members of Supervisory Committee

This is to confirm that:
- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: _____
Name of
Chairman of
Supervisory
Committee: <u>Prof. Ir. Dr. Mohd Amin Mohd Soom</u>

Signature: _____
Name of
Member of
Supervisory
Committee: <u>Prof. Dr. Thamer Ahmed Mohamed</u>

Signature: _____
Name of
Member of
Supervisory
Committee: <u>Assoc. Prof. Dr. Abdul Halim Ghazali</u>

Signature: _____
Name of
Member of
Supervisory
Committee: _____

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

xvii

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
CAT-Field	Coastal Aquifer Test Field
cm	Centimeter
CODESA-3D	Coupled Density-dependent variably Saturated flow and miscible transport 3D model
C_F	Concentration of Freshwater
DC	Direct Current
EC	Electrical Conductivity
EM	Electromagnetic Method
ERT	Electrical Resistivity Tomography
FEFLOW	Finite Element Subsurface Flow & Transport Simulation System.
FVUM	Finite Volume Unstructured Mesh
GA	Genetic Algorithms
GCG	Generalized Conjugate-Gradient Solver
GIS	Geographic Information System
GPR	Ground Penetrating Radar
h	Hours
IMT	Integrated MT3DMS Transport solver
IWTABLE	Water Table Correction
JICA	Japan International Cooperation Agency
KLIA	Kuala Lumpur International Airport
L_0	initial distance of seawater wedge
m	Meter

MAE	Mean Absolute Error
ME	Mean Error
MDGM	Minerals and Geosciences Department, Malaysia
MHz	Megahertz
mm	Millimeter
Mo	Month
MOC	Method of Characteristics
MOC3D	3D method-of-characteristics ground-water flow and transport model

CHAPTER 1

INTRODUCTION

1.1   General

In highly populated coastal areas, groundwater is regarded as a major source for freshwater. About 70% of global population lives in coastal regions. Population growth often increases over time. Population growth is a direct determinant of increase in water demands for domestic use. Furthermore, coastal regions are frequently heavily urbanized which results in a dramatic increase in the demand for water. With increasing demand for water, wherein the groundwater is perhaps most important source in coastal areas, the extractions of groundwater from coastal aquifer increases. Therefore, intensive groundwater abstraction alters the equilibrium between freshwater and saltwater with the net result of an inland movement of the wedge (seawater intrusion), and upward movement of saltwater below partially penetrating pumping wells (up-coning). Consequently, the intrusion of seawater into coastal aquifer results in degradation of groundwater quality.

The term saltwater intrusion is usually referred to the encroachment of saline water into a coastal aquifer whether the source of saline water is from the sea, or from other sources. If the source of this saline water is sea water, this phenomenon is defined as seawater intrusion. Seawater intrusion is a widespread contamination problem in coastal regions where fresh water aquifers are hydraulically connected with sea. The laws of physics demonstrated that seawater always tends to invade formation of the coastal aquifer because the density of seawater is slightly higher than freshwater density, further, dissolved salt concentration in seawater is much higher than freshwater (Camas, 2007; Elder, 1967). In addition, seawater intrusion occurs due to advection, dispersion and diffusion of the saline solute into freshwater body. Therefore, the dynamic movement of seawater inland into freshwater aquifers inevitably occurs whether under natural undisturbed conditions or under man-made conditions (Ma *et al.*, 2005).

Under man-made conditions, the seawater intrusion is more severe than under natural conditions. The man-made processes that induce seawater wedge to further advance inland are heavy pumping of groundwater, which permits the heavier saltwater to displace the lighter freshwater, and construction of a coastal drainage canal, which allows tidal water to move forward inland and infiltrate into the adjacent freshwater aquifer. Since the severe saltwater intrusion occurs mainly due to excessive groundwater withdrawals, this study was concerned with seawater intrusion due to over pumping of groundwater for agricultural, industrial and domestic uses in the coastal areas where the population is more dense.

Deterioration of freshwater quality in coastal aquifers caused by seawater intrusion is one of considerable concerns in coastal water resources management because saline water restricts use of freshwater from the invaded aquifers for the agricultural, industrial, and domestic purposes. To make sure that groundwater in coastal aquifers is suitable for its purpose; its quality can be evaluated by monitoring and modeling.

In simplest terms, the aim of groundwater monitoring and modeling is to assess the groundwater quality and the change of groundwater quality with time. Consequently, monitoring and modeling of saltwater intrusion into coastal aquifers are needed before initiating a major groundwater development program.

Permanent monitoring and modeling of the saltwater interface is necessary in determining proper management technique. The most important thing in determining proper control measures to mitigate seawater intrusion is an understanding of the mechanism of movement and mixing between freshwater and seawater. The reliance on constant monitoring only to understand the mechanism and movement of the saltwater interface is insufficient. Thus, seawater intrusion modeling provides a better understanding of the mechanism of movement and mixing between freshwater and seawater and the factors that affect these processes so as to manage and protect freshwater in the coastal aquifer for future use.

Groundwater flow and solute transport models play a vital role in modeling, understanding and decision–making for management and prevention of seawater intrusion. The groundwater flow and solute transport modeling are used to provide sustainable coastal aquifer management. Groundwater flow and solute transport models are one of various valuable tools to determine the current aquifer situations, to predict future aquifer conditions and are employed to establish remedial action plans to mitigate the groundwater quality degradation.

Three main classes of groundwater and solute transport models have been used by researchers to study seawater intrusion phenomenon. These models include: physical models, analogue models, including viscous analogue and electric analogues, and mathematical models, including analytical models and numerical models. With the advent of high-speed computational capabilities (digital computer) in 1960's, numerical models have been the superior type of model for studying complex groundwater flow and solute transport problems such as seawater intrusion phenomenon However, the development and application of these models that simulate groundwater flow and contamination problems such seawater intrusion is more difficult than those that simulate groundwater flow alone. The simulation of seawater intrusion into the coastal aquifers is considered difficult task as a result of variation of the water density and the salinity concentrations in the water substantially throughout the modeled coastal area. To overcome these difficulties, two approaches are used to simulate seawater intrusion (Kumar, 2006a). The first one is called sharp interface. In this approach, the contact zone between freshwater and saline water zones is assumed to be immiscible and separated by a sharp interface: This approach is referred to sharp interface (constant-density) model. In the second approach, the contact zone between freshwater and saline water is considered being a miscible zone (mixing zone/ miscible transport zone/ miscible disperse zone) having a spatially variable salt concentration that affects the fluid's density: This approach is referred to as density dependent flow approach or density-dependent groundwater flow and solute-transport model.

The sharp interface models are very useful for understanding the overall behavior of the system before applying the density dependent approach for examining the smaller scale effects. The sharp interface approach simplifies the seawater intrusion problem; however, it is not applicable for complex, real world seawater intrusion problem.

Therefore, the alternative for simulating this phenomenon is the concept of a density dependent model.

The density-dependent groundwater flow and solute transport (miscible transport/ miscible disperse) models describe the seawater intrusion mechanism due to strong saltwater hydrodynamic dispersion and the existence of a wide transition zone. Such models account for both advective and dispersive transport of saltwater. The ability of a model to realistically simulate the seawater intrusion phenomena, as density dependent flow and solute transport model can effectively increase its predictive capability regarding the true structure/configuration and position of the disperse interface (mixing zone). A set of numerical density dependent flow model codes has been developed to study seawater intrusion; however, their accuracy or validity is still being debated. It is noteworthy that there are considerable discrepancies in simulation results between numerical model codes for the same problem in previous studies (Werner *et al.*, 2013). This implies that different codes may produce different results for the same problem, due to differences in their governing equations and to numerical errors. The numerical models are approximative, and errors inevitably exist (Diersch & Kolditz, 2002). The major drawback of numerical models is that numerical errors are introduced during the computational simulations procedure. These errors include round-off error, truncation error, and numerical dispersion. All of these numerical errors affect the accuracy of the simulation results. They may lead to quantitative and even qualitative changes in simulation results, potentially affecting the management of field sites (Woods, 2004).

To reduce the uncertainty associated with numerical simulations, few benchmark problems have been developed for testing performance of density-dependent flow codes. They can provide assessments with respect to accuracy and reliability of numerical codes. These benchmarking problems include the Henry Problem (Henry, 1964), Elder Problem (Elder, 1967), and Hydrocoin Problem (Konikow *et al.*, 1997). However, each of these solutions has drawbacks and many unresolved issues remain with respect of accuracy of these benchmarking tests. In addition, the most common benchmarking problem in use concerning saltwater intrusion into coastal aquifer is saltwater Henry's solution. However, it has many drawbacks too and it remains questionable (Goswami & Clement, 2007; Simpson & Clement, 2004). A few laboratory models have also been used to investigate seawater intrusion problem based on density-dependent approach. However, they are based on small laboratory-scale physical model experiments and various forms of the Henry problem. Therefore, they could not provide in- sights into mixing-zone development, which can be illustrated by means of large scale model. Various forms of the Henry problem continued to be used as a replacement for seawater intrusion process understanding, and while this affords advantages of simplicity, the representativeness of the Henry problem to real-world seawater intrusion remains questionable. In addition, most of the previous laboratory studies and Henry's problem have been used to study seawater intrusion under steady state only (Chang & Clement, 2012).

1.2   Problem Statement

Seawater intrusion into coastal aquifers is one of the most challenging environmental issues faced by hydrologists, engineers and water resource planners especially with

the world experiencing climate change and global warming. Modelling seawater intrusion based on density dependent flow approach can play an important role in understanding and decision–making for control and prevention of such problems. Understanding the mixing dynamics of sea water within freshwater aquifer systems is extremely complex because physics of seawater-freshwater movement in coastal aquifers is difficult to conceptualize. To make sense the complexity, scientists and researchers have developed a variety of numerical density dependent flow models (computer codes) that describe the real seawater intrusion mechanism. Therefore, density dependent groundwater flow computer codes have become the favoured type of model for studying such a complex seawater intrusion problem. Unfortunately, there are difficulties and inconsistencies in previous studies that clearly show dependent density flow simulation can be problematic. These difficulties and inconsistencies are attributed to a number of issues that limit the accuracy and usefulness of numerical simulations of dependent-density groundwater flow and solute transport problems such seawater intrusion.

There is disagreement within the literature on the best choice of numerical computer model codes. Different codes might exhibit different solutions for the same problem because different codes do use a different form of governing equations, and different solution strategies and techniques. These numerical model computer codes are approximative, and errors inevitably occur. This means that there is an error or uncertainty in results inherent in the solutions from simulations performed with these computer codes. These inherent inaccuracies are due solely to the fact that we are approximating a continuous system by a finite length and discrete approximation. These numerical errors inherent in a code may lead to large quantitative or qualitative differences between the expected and simulated results unless extremely accurate solution techniques are used. Thus, the assessment of numerical errors is very important to test the accuracy of density dependent flow computer codes. The testing of models is performed by comparing model performance with so- called benchmark problems.

The availability of benchmark problems for testing these model codes is limited, and the existing benchmark problems are defined differently by different researchers. The agreeable solutions on these benchmark test problems are still subjected to debate and remain unsolved. For instance, saltwater intrusion Henry's solution is the most common benchmarking problem in use; however, it remains questionable. Thus, there are hard questions in this area that needs to be answered by investigators.

Henry problem is a semi-analytical solution which has not been reproduced in a physical model. In the classic Henry's problem, an important consideration is given to the assumption that saline water intrusion occurs in steady flows, which is resolved using semi-analytical technique developed by (Henry, 1964). Henry's analytical solution is highly controversial (Segol, 1994; Simpson & Clement, 2004). Over the past 50 years, Henry's problem has undergone several revisions that have included the use of different dispersion coefficients, both constant (Voss & Souza, 1987) and spatially variable (Frind, 1982), different outflow boundary conditions (Segol et al., 1975), and different freshwater recharge rates (Simpson & Clement, 2004). Several authors have improved the original Henry's analytical solution but it still not corresponds well with numerical solutions (the accurate solution), because of the inaccurate total dispersion coefficient, varying boundary conditions and different

diffusivities and inflow velocities that have been used by several analysts. In addition, a prominent drawback in the Henry problem is the fact that the model is typically unresponsive to coupled density-dependent problems because hydrodynamic dispersion is not taken into account. Therefore, the transition zone in original Henry's profiles surfaces as a result of increased molecular diffusion which to a considerable degree conceals the coupled density-dependent flow.

There is little progress in laboratory studies that can promote a better understanding of seawater intrusion mechanism based on density dependent approach where transport of salt by means of advection and hydrodynamic dispersion are taken into account, and they can provide confident verification for numerical density dependent flow computer codes. A few published laboratory studies include enough details for simulating seawater intrusion based on density dependent approach, but some drawbacks are associated with these studies. For instance, transient conditions were not taken into account, also mixing zone was considered as sharp interface, and many other drawbacks will be discussed later in Chapter 2.

Therefore, there is a need to simulate seawater intrusion based on density dependent approach experimentally and numerically to provide a better understanding of the movement and mixing between freshwater and saltwater, to produce experimental data sets that include a steady state seawater wedge data set, and transient seawater wedge data set which can then be used as an alternative benchmarking problem, which in turn result in enhancing the accuracy of the saltwater intrusion models. There is a need to analyse seawater intrusion control methods under steady state and transient conditions in order to manage and protect coastal aquifers for future use.

1.3 Hypothesis, Goal and Objectives

In this study, a hypothesis was proposed that the rate of freshwater flow may significantly influence the movement of the salt-wedge, and growth and decay of the mixing zone between freshwater and seawater. This hypothesis was examined by performing experimental and numerical simulations of seawater intrusion based on density dependent (mixing zone) approach in order to better understand the movement and mixing of freshwater and saltwater. Experimental data sets were produced under steady-state and transient conditions to be used as an alternative benchmarking solution. The movement of the salt-wedge and the development and decay of the mixing zone occur due to complex effects of the landward boundary. An example is the differences in fresh groundwater flow rates transmitted through the aquifer caused by seasonal variations in fresh groundwater heads. The advancement of salt-wedge and development of mixing zone can be created by reducing freshwater level at the landward boundary while receding salt-wedge and decay of the mixing zone can be caused by raising the freshwater level at the landward boundary.

The main goal of this study was to investigate the movement and the extent of seawater intrusion into coastal aquifers based on density-dependent approach (mixing zone) using physical and numerical models. This includes investigation of possibilities of control for seawater intrusion in the coastal aquifer under steady state and transient conditions and determination of aquifer parameters. A large scale

laboratory physical model aquifer (large flow tank) was constructed for experimental simulation of seawater intrusion and its controlling methods as well as for determining the aquifer parameters. Density dependent numerical model represented by SEAWAT computer code was selected for numerical simulation of seawater intrusion and its controlling methods.

The specific objectives of this study were as follows:

1. To simulate saltwater intrusion into an unconfined aquifer based on the density dependent approach (mixing zone) under steady state and transient state by using a well-controlled large scale laboratory model.
2. To simulate seawater intrusion in coastal aquifers by using SEAWAT-2000 computer model on the physical model scheme under steady state and transient state conditions, and under different hydraulic gradient conditions and compare the output of these simulations against the experimental data.
3. To simulate the seawater intrusion control in coastal aquifer under steady state and transient conditions using the methods of recharge by injection of freshwater and discharge by pumping of brackish water from the dispersion zone.
4. To develop a three dimensional density dependent numerical model based on SEAWAT-2000 code to assess the current and future situation of seawater intrusion into semi confined aquifer in the lowlands of Langat Basin, as a case study.

1.4 Scope of the Study

This work is a study on the seawater intrusion due to over pumping of groundwater for agricultural, industrial and domestic uses in the coastal areas where the population is more dense as an important real world issue in the field of water resources management. The scope of this study is to simulate seawater intrusion as induced by human interventions (over-pumping) based on density dependent approach. It focuses on gaining insight into the complex, real world seawater intrusion problem caused by advection and strong saltwater hydrodynamic dispersion, enhancing the accuracy of the numerical density dependent model codes through generating experimental data sets for alternative benchmarking, and analyzing of the fresh water injection and brackish water pumping methods.

The study is a major contribution to knowledge in the continuous quest by researchers in the development of density-dependent groundwater flow and solute transport models. The study compiles tools and techniques that include laboratory scale experiments and density dependent groundwater flow and solute transport numerical modeling, to provide a meaningful solution to seawater intrusion in the coastal aquifer.

In this study, a well–equipped large laboratory scale physical aquifer model was developed to simulate and control seawater intrusion based on density dependent approach under steady state and transient state conditions. The density dependent flow numerical model code SEAWAT-2000 (Bear *et al.*, 1999) was applied to simulate the steady state and transient experiments. This was to test whether the experimental data are consistent with the predictions made by this widely used

numerical model. A three dimensional density dependent numerical model based on SEAWAT-2000 code was developed to simulate seawater intrusion into a semi confined aquifer in the lowlands of Langat basin, Selangor, Malaysia as a case study.

1.5   Significance of the Study

The significance of the study lies in the development of the experimental setup of a well–equipped large laboratory scale physical aquifer model that provides a novel approach for simulating seawater intrusion based on density dependent approach. This in turn provides a better understanding of the mechanism of movement and mixing between fresh and saline water and the factors influencing these processes. This will aid in managing and protecting freshwater resources for future use, and create new opportunities for enhancing the accuracy of the saltwater intrusion models. This work provides a set of new benchmark data sets for testing saltwater intrusion numerical models, which will greatly benefit the density dependent flow and solute transport modeling community throughout the provision of accurate solution to the saltwater intrusion problem, which can then be used as an alternative benchmarking solution. This new benchmarking is a more robust alternative to the original Henry's problem since it considers saltwater transport under both steady state and transient conditions, and due to both advection and hydrodynamic dispersion.

The development of a three dimensional (3D) density dependent numerical model based on SEAWAT-2000 code, which constitutes one of the most comprehensive and versatile state-of-the-art software packages for investigating seawater intrusion, is considered as a valuable contribution because it provided a clear picture of the current and future situation of seawater intrusion into the lowland Langat basin's aquifer. The outputs of this model provide some insights and information to water resource planners and decision makers in the Langat basin, on how to establish remedial action plans to attenuate the groundwater quality deterioration. Consequently, the developed numerical model would aid in choosing the most suitable control method in order to prevent the advancement of seawater into the main aquifer. Moreover, this model contributes to improve understanding of the dynamic process of seawater intrusion in the studied area, which in turn will contribute to water resource management policy in Langat basin. The outcomes of this model can be considered as a foundation which can be used in other coastal aquifers under similar hydrogeological conditions in order to protect the coastal water resources.

1.6   Thesis Organization

This thesis is organized into five chapters. Chapter 1 gives the background of the seawater intrusion into coastal aquifers. It also discusses seawater intrusion modeling. The objectives and significance of the study are presented in this chapter. Chapter 2 is the literature review which presents in-depth discussions of groundwater, groundwater contamination, groundwater modeling, seawater intrusion problem, methods of investigating seawater intrusion, seawater intrusion modeling,

seawater intrusion numerical models shortcomings and benchmarking, and seawater intrusion control measures. The general methodology adopted in this research in order to achieve the objectives is described in Chapter 3. The results and discussions are presented in Chapter 4. In Chapter 5, a summary of the work is presented, suggestions of possible areas of improvement are given, and some conclusions from the study are highlighted.

1.8

REFERENCES

Abarca, E., & Clement, T. P. (2009). A novel approach for characterizing the mixing zone of a saltwater wedge. *Geophysical Research Letters, 36*(6).

Abarca, E., Vázquez-Suñé, E., Carrera, J., Capino, B., Gámez, D., & Batlle, F. (2006). Optimal design of measures to correct seawater intrusion. *Water Resources Research, 42*(9).

Abd-Elhamid, H. F. (2010). *A simulation-optimization model to study the control of seawater intrusion in coastal aquifers.* PhD thesis, University of Exeter.

Abdul Nassir, S., Loke, M., Lee, C., & Nawawi, M. (2000). Salt-water intrusion mapping by geoelectrical imaging surveys. *Geophysical prospecting, 48*(4), 647-661.

Abdullah, M. H., Raveena, S. M., & Aris, A. Z. (2010). A numerical modelling of seawater intrusion into an oceanic island aquifer, Sipadan Island, Malaysia. *Sains Malaysiana, 39*(4), 525-532.

Ackerer, P., Younes, A., & Mose, R. (1999). Modeling variable density flow and solute transport in porous medium: 1. Numerical model and verification. *Transport in porous media, 35*(3), 345-373.

Acworth, R., & Dasey, G. (2003). Mapping of the hyporheic zone around a tidal creek using a combination of borehole logging, borehole electrical tomography and cross-creek electrical imaging, New South Wales, Australia. *Hydrogeology Journal, 11*(3), 368-377.

Aiba, M. (1983). Irrigation Water Resources Development Project by Groundwater Storage Dam, Civil Engineering in Japan, Vol. 22, No. 12, Dec, 1983, pp. 152-163.

Aiken, S. R., Leigh, C. H., Leinbach, T., & Moss, M. (1982). *Development and environment in Peninsular Malaysia*: McGraw-Hill International Book Company Singapore.

Albouy, Y., Andrieux, P., Rakotondrasoa, G., Ritz, M., Descloitres, M., Join, J. L., & Rasolomanana, E. (2001). Mapping Coastal Aquifers by Joint Inversion of DC and TEM Soundings-Three Case Histories. *Ground Water, 39*(1), 87-97.

Alf, G., Angela, H., Martin, L., Berthold, R., & Andre, S. (2002). *Numerical and hydrochemical modelling of saltwater intrusion into a pleistocrnr aquifer-case study Grobbeuthen, Brandenburg.* Paper presented at the Proceeding of the 17th Salt Water Intrusion Meeting., Delft, the Netherlands.

Aliewi, A., Mackay, R., Jayyousi, A., Nasereddin, K., Mushtaha, A., & Yaqubi, A. (2001). Numerical simulation of the movement of saltwater under skimming

and scavenger pumping in the Pleistocene aquifer of Gaza and Jericho areas, Palestine. *Transport in porous media, 43*(1), 195-212.

Allow, K. A. (2011). The use of injection wells and a subsurface barrier in the prevention of seawater intrusion: a modelling approach. *Arabian Journal of Geosciences, 5*(5), 1151-1161.

Amaziane, B., Cheng, A. H.-D., Naji, A., & Ouazar, D. (2004). *Stochastic optimal pumping under no-intrusion constraints in coastal aquifers.* . Paper presented at the Proceeding of the 18th Salt Water Intrusion Meeting, Cartagena (Spain).

Anderson, M. P., & Woessner, W. W. (1992). *Applied groundwater modeling: simulation of flow and advective transport*: San Diego, Calif., Academic Press, Inc., 381 p. Access Online via Elsevier.

Anthony, S. S. (1992). Electromagnetic methods for mapping freshwater lenses on Micronesian atoll islands. *Journal of Hydrology, 137*(1), 99-111.

Anwar, H. (1983). The effect of a subsurface barrier on the conservation of freshwater in coastal aquifers. *Water Research, 17*(10), 1257-1265.

Badon-Ghyben, W. (1888). Nota in verband met de voorgenomen putboring nabij Amsterdam (Notes on the probable results of well drilling near Amsterdam). *Tijdschrift van het Koninklijk Instituut van Ingenieurs, The Hague, 9*, 8-22.

Bajjali, W. (2012). Model the effect of four artificial recharge dams on the quality of groundwater using geostatistical methods in GIS environment, Oman. *Journal of Spatial Hydrology, 5*(2).

Bakker, M. (1998). Transient Dupuit interface flow with partially penetrating features. *Water Resources Research, 34*(11), 2911-2918.

Bakker, M. (2006). Analytic solutions for interface flow in combined confined and semi-confined, coastal aquifers. *Advances in Water Resources, 29*(3), 417-425.

Bakker, M., Oude Essink, G. H., & Langevin, C. D. (2004). The rotating movement of three immiscible fluids—a benchmark problem. *Journal of Hydrology, 287*(1), 270-278.

Barlow, P. M. (2003). *Ground water in freshwater-saltwater environments of the Atlantic coast* (Vol. 1262): Geological Survey (USGS).

Barreto, J., Nuno, M. A., & Haie, N. (2001). *Modelling of rural usage of groundwater subject to saltwater intrusion.* Paper presented at the Proceeding of the 1st international conference and workshop on saltwater intrusion and coastal aquifers, monitoring, modelling,and management. , (Morocco).

Barrett, B., Heinson, G., Hatch, M., & Telfer, A. (2002). Geophysical methods in saline groundwater studies: locating perched water tables and fresh-water lenses. *Exploration Geophysics, 33*(2), 115-121.

Barrocule, G., Cau, P., Soddu, S., & Uras, G. (2005). Predicting groundwater salinity changes in the coastal aquifer of Arborea (Central—Western Sardinia). *Groundwater and saline intrusion*(15), 243.

Basdurak, N. B., Onder, H., & Motz, L. H. (2007). *Analysis of Techniques to Limit Saltwater Intrusion in Coastal Aquifers*.

Basri, M. H. (2001). *Two new methods for optimal design of subsurface barrier to control seawater intrusion. Ph.D. thesis, Univ. of Manitoba, Canada.*

Bear, J. (1961). Some experiments in dispersion. *Journal of Geophysical Research, 66*(8), 2455-2467.

Bear, J. (1988). *Dynamics of fluids in porous media*: Dover publications.

Bear, J. (2012). *Hydraulics of groundwater*: DoverPublications. com.

Bear, J., Cheng, A., Sorek, S., Ouazar, D., & Herrera, I. (1999). *Seawater Intrusion in Coastal Aquifers Concepts, Methods and Practices*: Springer.

Bear, J., & Cheng, A. H. D. (2010). *Modeling groundwater flow and contaminant transport*: Springer.

Bear, J., & Dagan, G. (1964b). Some exact solutions of interface problems by means of the hydrograph method. *J.Geophys. Res., 69*(8), 1563-1572.

Bear, J., & Verruijt, A. (1987). *Modeling groundwater flow and pollution* (Vol. 2): Springer.

Bedient, P. B., Rifai, H. S., & Newell, C. J. (1994). *Ground water contamination: transport and remediation*: PTR Prentice Hall.

Blake, G., Hartge, K., & Klute, A. (1986). Methods of soil analysis: Physical and mineralogical methods. *Methods of soil analysis: Physical and mineralogical methods, 1*.

Bobba, A. (1993). Field validation of 'SUTRA'groundwater flow model to Lambton County, Ontario, Canada. *Water resources management, 7*(4), 289-310.

Bocanegra, E. M., & Massone, H. E. (2004). *Exploitation of coastal aquifers in Latin America and the Caribbean. Problems and solutions.* Paper presented at the 18th Salt Water Intrusion Meeting (18th SWIM), Cartagena, Spain.

Bolster, D. T., Tartakovsky, D. M., & Dentz, M. (2007). Analytical models of contaminant transport in coastal aquifers. *Advances in water resources, 30*(9), 1962-1972.

Bray, B. S., & Yeh, W. W.-G. (2008). Improving seawater barrier operation with simulation optimization in southern California. *Journal of water resources planning and management, 134*(2), 171-180.

Buckley, D. K., Hinsby, K., & Manzano, M. (2001). Application of geophysical borehole logging. *Geological Society, London, Special Publications, 189*.

Bugg, S. F., & Lloyd, J. W. (1976). A study of fresh water lens configuration in the Cayman Islands using resistivity methods. *Quarterly Journal of Engineering Geology and Hydrogeology, 9*(4), 291-302.

Camas, B. S. (2007). *Saltwater Intrusion Simulation in Heterogeneous Aquifer Using Lattice Boltzmann Method.* Polytechnic University.

Canale, R., & Chapra, S. (2002). Numerical Methods for Engineers: with Software and Programming Applications: McGraw-Hill, New York.

Carey, H., Lenkopane, M., Werner, A., Li, L., & Lockington, D. (2009). Tidal controls on coastal groundwater conditions: field investigation of a macrotidal system. *Australian Journal of Earth Sciences, 56*(8), 1165-1179.

Chang, S. W., & Clement, T. P. (2012). Experimental and numerical investigation of saltwater intrusion dynamics in flux-controlled groundwater systems. *Water Resources Research, 48*(9).

Charbeneau, R. J. (2006). *Groundwater Hydraulics And Pollutant Transport*: Waveland Press, Incorporated.

Cheng, A., & Quazar, D. (1999). Analytical solutions. In A. Cheng, S. Sorek, D. Quazar & I. Herrera (Eds.), *Seawater intrusion in coastal aquifers.* (pp. 163-191). Dordrecht: Kluwer Publishers.

Cheng, A. H. D., & Ouazar, D. (2003). *Coastal Aquifer Management-Monitoring, Modeling, and Case Studies*: Taylor & Francis.

Cheng, J.-R., Strobl, R. O., Yeh, G.-T., Lin, H.-C., & Choi, W. H. (1998). Modeling of 2D density-dependent flow and transport in the subsurface. *Journal of Hydrologic Engineering, 3*(4), 248-257.

Cherubini, C., & Pastore, N. (2011). Critical stress scenarios for a coastal aquifer in southeastern Italy. *Natural Hazards and Earth System Science, 11*(5), 1381-1393.

Cobaner, M., Yurtal, R., Dogan, A., & Motz, L. H. (2012). Three dimensional simulation of seawater intrusion in coastal aquifers: A case study in the Goksu Deltaic Plain. *Journal of Hydrology*.

Collins, M. A., & Gelhar, L. W. (1971). Seawater intrusion in layered aquifers. *Water Resources Research, 7*(4), 971-979.

Contractor, D. N. (1983). Numerical modeling of saltwater intrusion in the northern Guam lens1. *JAWRA Journal of the American Water Resources Association, 19*(5), 745-751.

Contractor, D. N., & Srivastava, R. (1990). Simulation of saltwater intrusion in the Northern Guam Lens using a microcomputer. *Journal of Hydrology, 118*(1), 87-106.

Cooper, H. H. (1959). A hypothesis concerning the dynamic balance of fresh water and salt water in a coastal aquifer. *Journal of Geophysical Research, 64*(4), 461-467.

Croucher, A., & O'sullivan, M. (1995). The Henry problem for saltwater intrusion. *Water Resources Research, 31*(7), 1809-1814.

Custodio, E. (1987). Seawater intrusion in the Llobregat Delta, near Barcelona (Catalonia, Spain). *Groundwater problems in coastal areas. Studies and reports in hydrogeology*(45), 436-463.

Custodio, E., & Bruggeman, G. (1987). *Groundwater problems in coastal areas. Publication of the IHP Working Group on Changes in the Salt-fresh Water Balance in Deltas, Estuaries and Coastal Zones due to Structural Works and Groundwater Exploitation*.

Dagan, G., & Bear, J. (1968). Solving the problem of local interface upconing in a coastal aquifer by the method of small perturbations. *Journal of Hydraulic Research, 6*(1), 15-44.

Dagan, G., & Zeitoun, D. G. (1998). Seawater-freshwater interface in a stratified aquifer of random permeability distribution. *Journal of Contaminant Hydrology, 29*(3), 185-203.

Dahlin, T., Leroux, V., & Nissen, J. (2002). Measuring techniques in induced polarisation imaging. *Journal of Applied Geophysics, 50*(3), 279-298.

Dausman, A. M., Doherty, J., Langevin, C. D., & Dixon, J. (2010). Hypothesis testing of buoyant plume migration using a highly parameterized variable-density groundwater model at a site in Florida, USA. *Hydrogeology Journal, 18*(1), 147-160.

Dausman, A. M., Langevin, C., Bakker, M., & Schaars, F. (2010). A comparison between SWI and SEAWAT-The importance of dispersion, inversion and vertical anisotropy. *Proceedings of SWIM, 21*, 2010.

Day-Lewis, F., White, E., Johnson, C., Lane Jr, J., & Belaval, M. (2006). Continuous resistivity profiling to delineate submarine groundwater discharge—Examples and limitations. *The Leading Edge, 25*(6), 724-728.

De Breuck, W., & De Moor, G. (1969). The water-table aquifer in the eastern Coastal Area of Belgium. *Hydrological Sciences Journal, 14*(3), 137-155.

De Franco, R., Biella, G., Tosi, L., Teatini, P., Lozej, A., Chiozzotto, B., . . . Mayer, A. (2009). Monitoring the saltwater intrusion by time lapse electrical resistivity tomography: The Chioggia test site (Venice Lagoon, Italy). *Journal of Applied Geophysics, 69*(3), 117-130.

R.5

Dentz, M., Tartakovsky, D. M., Abarca, E., Guadagnini, A., Sa `nchez-Vila, X., & Carrera, J. (2006). Perturbation analysis of variable density flow in porous media, J. Fluid Mech., 561, 209–235.

Diersch, H. J. G. (1988). Finite element modelling of recirculating density-driven saltwater intrusion processes in groundwater. *Advances in water resources, 11*(1), 25-43.

Diersch, H. J. G. (1996). Interactive, graphics-based finite-element simulation system FEFLOW for modeling groundwater flow, contaminant mass and heat transport processes, FEFLOW User's Manual Version 4.5.

Diersch, H. J. G. (2002). FEFLOW: finite element subsurface flow & transport simulation system—reference manual. *WASY GmbH Institute for Water Resources Planning and Systems Research, Berlin*.

Diersch, H. J. G. (2005). FEFLOW finite element subsurface flow and transport simulation system. *Reference manual. Berlin, Germany: WASY GmbH*.

Diersch, H. J. G., & Kolditz, O. (2002). Variable-density flow and transport in porous media: approaches and challenges. *Advances in water resources, 25*(8), 899-944.

Domenico, P. A., & Schwartz, F. W. (1990). Physical and chemical hydrology. *Text Book*.

Ekwurzel, B., Moran, J., Hudson, G., Bissani, M., Blake, R., Krimissa, M., . . . Hsissou, Y. (2001). *An isotopic investigation of salinity and water sources in the Souss-Massa Basin, Morocco.* Paper presented at the The first international conference on salt water intrusion and coastal aquifers. Essaouira, Morocco.

El-Bihery, M. A. (2009). Groundwater flow modeling of Quaternary aquifer Ras Sudr, Egypt. *Environmental geology, 58*(5), 1095-1105.

Elder, J. (1967). Transient convection in a porous medium. *J. Fluid Mech, 27*(3), 609-623.

Essaid, H. I. (1990). *The computer model SHARP, a quasi-three-dimensional finite-difference model to simulate freshwater and saltwater flow in layered coastal aquifer systems*: Department of the Interior, US Geological Survey.

Essink, G. H. O. (2001a). Improving fresh groundwater supply—problems and solutions. *Ocean & coastal management, 44*(5), 429-449.

Essink, G. H. O. (2001b). Salt water intrusion in a three-dimensional groundwater system in the Netherlands: a numerical study. *Transport in porous media, 43*(1), 137-158.

Essink, G. H. O. (2001c). Saltwater intrusion in 3D large-scale aquifers: a Dutch case. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, 26*(4), 337-344.

Essink, G. H. O., Van Baaren, E., & De Louw, P. (2010). Effects of climate change on coastal groundwater systems: a modeling study in the Netherlands. *Water Resources Research, 46*(10).

Essink, O. G. H. P. (1998). *MOC3D adapted to simulate 3D density-dependent groundwater flow.* Paper presented at the Proc. MODFLOW'98 Conf., Golden, Colorado, USA, pp. 291–303.

Fitterman, D. V., & Deszcz-Pan, M. (1998). Helicopter EM mapping of saltwater intrusion in Everglades National Park, Florida. *Exploration Geophysics, 29*(2), 240-243.

Fitterman, D. V., & Deszcz-Pan, M. (2001). *Using airborne and ground electromagnetic data to map hydrologic features in Everglades National Park.* Paper presented at the Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems SAGEEP.

Fitterman, D. V., & Stewart, M. T. (1986). Transient electromagnetic sounding for groundwater. *Geophysics, 51*(4), 995-1005.

Flathe, H. (1955). Possibilities and limitations in applying geoelectrical methods to hydrogeological problems in the coastal areas of North West Germany. *Geophysical prospecting, 3*(2), 95-109.

Freeze, R. A., & Cherry, J. A. (1979). *Groundwater*: Prentice-Hall.

Fretwell, J. D., & Stewart, M. T. (1981). Resistivity study of a coastal karst terrain, Florida. *Ground Water, 19*(2), 156-162.

Frind, E. O. (1982). Simulation of long-term transient density-dependent transport in groundwater. *Advances in water resources, 5*(2), 73-88.

Frohlich, R. K., & Urish, D. W. (2002). The use of geoelectrics and test wells for the assessment of groundwater quality of a coastal industrial site. *Journal of Applied Geophysics, 50*(3), 261-278.

Frohlich, R. K., Urish, D. W., Fuller, J., & O'Reilly, M. (1994). Use of geoelectrical methods in groundwater pollution surveys in a coastal environment. *Journal of Applied Geophysics, 32*(2), 139-154.

Frolov, A., Khublaryan, M., & Mosolova, T. Y. (1994). The coastline geometry effect on sea water intrusion into aquifers. *Water Resources*.

Galeati, G., Gambolati, G., & Neuman, S. (1992). Coupled and partially coupled Eulerian-Lagrangian model of freshwater-seawater mixing. *Water Resources Research, 28*(1), 149-165.

Gambolati, G., Putti, M., & Paniconi, C. (1999). Three-dimensional model of coupled density-dependent flow and miscible salt transport *Seawater Intrusion in Coastal Aquifers—Concepts, Methods and Practices* (pp. 315-362): Springer.

Ganesan, M., & Thayumanavan, S. (2009). Management Strategies for a Seawater Intruded Aquifer System. *Journal of Sustainable Development, 2*(1), P94.

Georgopoulou, E., Kotronarou, A., Koussis, A., Restrepo, P. J., Gómez-Gotor, A., & Rodriguez Jimenez, J. J. (2001). A methodology to investigate brackish groundwater desalination coupled with aquifer recharge by treated wastewater as an alternative strategy for water supply in Mediterranean areas. *Desalination, 136*(1), 307-315.

Giambastiani, B., Antonellini, M., Oude Essink, G. H., & Stuurman, R. J. (2007). Saltwater intrusion in the unconfined coastal aquifer of Ravenna (Italy): a numerical model. *Journal of Hydrology, 340*(1), 91-104.

Ginsberg, A., & Levanton, A. (1976). Determination of saltwater interface by electrical resistivity sounding. *Hydrological science bulletin, 21*, 561-568.

Glover, R. (1959). The pattern of fresh-water flow in a coastal aquifer. *Journal of Geophysical Research, 64*(4), 457-459.

Goldman, M., Gilad, D., Ronen, A., & Melloul, A. (1991). Mapping of seawater intrusion into the coastal aquifer of Israel by the time domain electromagnetic method. *Geoexploration, 28*(2), 153-174.

Gossel, W., Sefelnasr, A., & Wycisk, P. (2010). Modelling of paleo-saltwater intrusion in the northern part of the Nubian Aquifer System, Northeast Africa. *Hydrogeology Journal, 18*(6), 1447-1463.

Goswami, R., Ambale, B., & Clement, T. (2009). Estimating errors in concentration measurements obtained from image analysis. *Vadose Zone Journal, 8*(1), 108-118.

Goswami, R. R., & Clement, T. P. (2007). Laboratory-scale investigation of saltwater intrusion dynamics. *Water Resources Research, 43*(4), W04418.

Gotovac, H., Andricevic, R., & Vranjes, M. (2001). *Effects of aquifer heterogeneity on the intrusion of sea water.* Paper presented at the Proceedings of the First International Conference on Salt Water Intrusion and Coastal Aquifers, Monitoring, Modelling and Management, Essaouira, Morocco.

Guo, W., & Bennett, G. (1998). SEAWAT version 1.1—A computer program for simulations of ground water flow of variable density. *A report prepared by Missimer International Inc.*

Guo, W., & Langevin, C. D. (2002). *User's guide to SEAWAT: A computer program for simulation of three-dimensional variable-density ground-water flow*: US Department of the Interior, US Geological Survey.

Gurdu, F., Motz, L. H., & Yurtal, R. (2001). *Simulation of seawater intrusion in the Goksu Delta at Silifke, Turkey.* Paper presented at the Proceedings of the First International Conference on Salt Water Intrusion and Coastal Aquifers, Monitoring, Modelling and Management, Essaouira, Morocco

Hallenbach, F. (1953). Geoeelectrical problems of the hydrology of west german areas* *Geophysical prospecting, 1*(4), 241-249.

Hamidi, M., & Yazdi, S.-R. (2008). Modeling of 2D density-dependent flow and transport in porous media using finite volume method. *Computers & Fluids, 37*(8), 1047-1055.

Harikrishna, K., Naik, D. R., Rao, T. V., Jaisankar, G., & Rao, V. V. (2012). A Study on Saltwater Intrusion Around Kolleru Lake, Andhra Pradesh, India. *International Journal of Engineering and Technology, 4*.

Harne, S., Chaube, U., Sharma, S., Sharma, P., & Parkhya, S. (2006). Mathematical modelling of salt water transport and its control in groundwater. *Natural and science, 4*(4), 32-39.

Helfferich, F. (1966). Ion exchange kinetics, in (ed), Ion exchange: A series of advances, vol. 1: Marcel Dekker, New York.

Henderson, R. D., Day-Lewis, F. D., Abarca, E., Harvey, C. F., Karam, H. N., Liu, L., & Lane Jr, J. W. (2010). Marine electrical resistivity imaging of submarine groundwater discharge: sensitivity analysis and application in Waquoit Bay, Massachusetts, USA. *Hydrogeology Journal, 18*(1), 173-185.

Henry, H. R. (1959). Salt intrusion into fresh-water aquifers. *Journal of Geophysical Research, 64*(11), 1911-1919.

Henry, H. R. (1964). Effects of dispersion on salt encroachment in coastal aquifers. *US Geol. Surv. Water Supply Pap, 1613*, C71-C84.

Herbert, A., Jackson, C., & Lever, D. (1988). Coupled groundwater flow and solute transport with fluid density strongly dependent upon concentration. *Water Resources Research, 24*(10), 1781-1795.

Herzberg, A. (1901). Die Wasserversorgung einiger Nordseebäder [The water supply on parts of the North Sea coast] J. *Gasbeleucht. u. Wasserversorg., Jahrg, 44*.

Hogan, M. B. (2006). *Understanding the flow and mixing dynamics of saline water discharged into coastal freshwater aquifers.* Degree of Master of Science Auburn University.

Hong, S.-H., Song, S.-H., Bae, S. K., & Park, N. (2004). Verification and validation of an optimization model for groundwater development in coastal areas. *Proceeding of 18th SWIM*, 77-90.

Hubbert, M. K. (1940). The theory of ground-water motion. *The Journal of Geology*, 785-944.

Huyakorn, P. S., Andersen, P. F., Mercer, J. W., & White, H. O. (1987). Saltwater intrusion in aquifers: Development and testing of a three-dimensional finite element model. *Water Resources Research, 23*(2), 293-312.

Hwang, S., Shin, J., Park, I., & Lee, S. (2004). Assessment of seawater intrusion using geophysical well logging and electrical soundings in a coastal aquifer, Youngkwang-gun, Korea. *Exploration Geophysics, 35*(1), 99-104.

Ibrahim, A., Harith, Z., & Nawawi, M. (2003). Resistivity imaging and borehole investigation of the Banting area aquifer, Selangor, Malaysia. *Journal of Environmental Hydrology, 11(10)*, 7.

Ibrahim, A., Nawawi, M., Harith, Z., & Ayub, M. (2002). *Mapping of groundwater aquifer using intergrated geophysical methods.* . Paper presented at the Proceedings of the Regional Symposium on Environment and Natural Resources, Hotel Renaissance Kuala Lumpur, Malaysia. 177 -187.

Igroufa, S., Hashim, R., & Taib, S. (2010). Mapping of salt-water intrusion by geoelectrical imaging in Carey Islands, from http://eprints.um.edu.my/3185/

Inouchi, K., Kishi, Y., & Kakinuma, T. (1985). The regional unsteady interface between fresh water and salt water in a confined coastal aquifer. *Journal of Hydrology, 77*(1), 307-331.

Istok, J. (1989). *Groundwater modeling by the finite element method* (Vol. 13): American Geophysical Union.

Javadi, A., Abd-Elhamid, H., & Farmani, R. (2012). A simulation-optimization model to control seawater intrusion in coastal aquifers using abstraction/recharge wells. *International Journal for Numerical and Analytical Methods in Geomechanics, 36*(16), 1757-1779.

Jiangong, W., Desan, Z., & Mingchuan, J. (1993, Nov. 1992). *Sea water intrusion and its control in the Shandong coastal zone, eastern China.* Paper presented at the Proceedings 12th Saltwater Intrusion Meeting. , Barcelona.

JICA, & MDGM. (2002). The study on the sustainable groundwater resources and environmental management for the Langat Basin in Malaysia. *Kuala Lumpur.*

JICA, & MGDM. (2002). The study on the sustainable groundwater resources and environmental management for the Langat Basin in Malaysia. Report, volume: 1-5, MGDM, Kuala Lumpur Malayisa.

Johannsen, K. (2002). The Elder problem—bifurcations and steady state solutions. *Developments in Water Science, 47*, 485-492.

Johnson, T., & Spery, M. (2001). *Direct potable use of intruded seawater from west coast basin aquifers, Los Angeles country, California.* Paper presented at the Proceeding of the 1st international conference and workshop on saltwater intrusion and coastal aquifers, monitoring, modelling, and management (Morocco).

Jones, B., Vengosh, A., Rosenthal, E., & Yechieli, Y. (1999). Geochemical investigations *Seawater Intrusion in Coastal Aquifers—Concepts, Methods and Practices* (pp. 51-71): Springer.

Kacimov, A., Sherif, M., Perret, J., & Al-Mushikhi, A. (2009). Control of sea-water intrusion by salt-water pumping: Coast of Oman. *Hydrogeology Journal, 17*(3), 541-558.

Kaleris, V. K., & Ziogas, A. I. (2012). The effect of cutoff walls on saltwater intrusion and groundwater extraction in coastal aquifers. *Journal of Hydrology*.

Kallioras, A., Pliakas, F.-K., Schuth, C., & Rausch, R. (2013). Methods to Countermeasure the Intrusion of Seawater into Coastal Aquifer Systems. *In S. K.,Sharma, & R., Sanghi, (Eds.), Wastewater Reuse and Management* (pp. 479-490): Springer.

Kashaigili, J., Mashauri, D., & Abdo, G. (2003). Groundwater management by using mathematical modeling: case of the Makutupora groundwater basin in dodoma Tanzania. *Botswana Journal of Technology, 12*(1), 19-24.

Kashef, A.-A. I. (1976). Control of salt-water intrusion by recharge wells. *Journal of the Irrigation and Drainage Division, 102*(4), 445-457.

Kashef, A.-A. I. (1986). *Groundwater engineering*: McGraw-Hill New York et al.

Kauahikaua, J. (1987). *Description of a fresh water lens at Laura island, Majuro atoll, Republic of the Marshall Islands, using electromagnetic profiling*: US Geological Survey.

Keller, G. V., & Frischknecht, F. C. (1966). Electrical methods in geophysical prospecting.

Kirkegaard, C., Sonnenborg, T. O., Auken, E., & Jørgensen, F. (2011). Salinity distribution in heterogeneous coastal aquifers mapped by airborne electromagnetics. *Vadose Zone Journal, 10*(1), 125-135.

Kohout, F. A. (1964). The flow of fresh water and salt water in the Biscayne aquifer of the Miami area, Florida. *Sea Water in Coastal Aquifers. US Geological Survey Water-Supply Paper*, 12-32.

Konikow, L. (1996). Use of numerical models to simulate groundwater flow and transport. *US Geological Survey*.

Konikow, L., Sanford, W., & Campbell, P. (1997). Constant-concentration boundary condition: lessons from the HYDROCOIN variable-density groundwater benchmark problem. *Water Resources Research, 33*(10), 2253-2261.

Konikow, L. F. (1977). Modeling chloride movement in the alluvial aquifer at the Rocky Mountain Arsenal, Colorado. USGS Water Supply Paper 2044, p 43.

Konikow, L. F., & Bredehoeft, J. D. (1978). *Computer model of two-dimensional solute transport and dispersion in ground water*: US Government Printing Office.

Konz, M., Ackerer, P., Meier, E., Huggenberger, P., Zechner, E., & Gechter, D. (2008). On the measurement of solute concentrations in 2-D flow tank experiments. *Hydrology and Earth System Sciences Discussions, 12*(3), 727-738.

Kourakos, G., & Mantoglou, A. (2009). Pumping optimization of coastal aquifers based on evolutionary algorithms and surrogate modular neural network models. *Advances in water resources, 32*(4), 507-521.

Kourakos, G., & Mantoglou, A. (2011). Simulation and multi-objective management of coastal aquifers in semi-arid regions. *Water resources management, 25*(4), 1063-1074.

Kuan, W. K., Jin, G., Xin, P., Robinson, C., Gibbes, B., & Li, L. (2012). Tidal influence on seawater intrusion in unconfined coastal aquifers. *Water Resources Research, 48*(2).

Kumar, C. (2006a). Management of groundwater in salt water ingress coastal aquifers. *Groundwater Modelling and Management, Capital Publishing company, New Delhi*, 540-560.

Kumar, C. (2006b). Management of groundwater in salt water ingress coastal aquifers *Groundwater Modelling and Management, Capital Publishing company, New Delhi* (pp. 540-560).

Langevin, C. D. (2001). Simulation of ground-water discharge to Biscayne Bay, southeastern Florida: United States Geological Survey.

Langevin, C. D., & Guo, W. (2006). MODFLOW/MT3DMS–Based Simulation of Variable-Density Ground Water Flow and Transport. *Ground Water, 44*(3), 339-351.

Langevin, C. D., Shoemaker, W. B., & Guo, W. (2003). *Modflow-2000: The US Geological Survey Modular Ground-water Model--documentation of the SEAWAT-2000 Version with the Variable-density Flow Process (VDF) and the Integrated MT3DMS Transport Process (IMT)*: US Department of the Interior, US Geological Survey.

Larabi, A., & De Smedt, F. (1997). Numerical solution of 3-D groundwater flow involving free boundaries by a fixed finite element method. *Journal of Hydrology, 201*(1), 161-182.

Lazar, A., Gvirtzman, H., & Yechieli, Y. (2004). *Freshwater-salinewater interface fluctuation in coastal aquifer due to sea tide.* Paper presented at the Proceeding of the 18th Salt Water Intrusion Meeting, Cartagena (Spain).

Lee, C.-H., & Cheng, R. T.-S. (1974). On seawater encroachment in coastal aquifers. *Water Resources Research, 10*(5), 1039-1043.

Lester, B. (1991). Lester, B., SWICHA, A Three-Dimensional Finite-Element Code for Analyzing Seawater Intrusion in Coastal Aquifers, Version 5.05.

GeoTrans, Inc., Sterling, Virginia, U.S.A., IGWMC, International Ground Water Modeling Center, Delft, the Netherlands, 178 pp.

Levi, E., Goldman, M., Shalem, Y., Weinstein, Y., YechieliY, & Herut, B. (2010). *Combined ERT-TDEM measurementsfor delineating salinewater intrusions from an estuarine riverinto the adjacent aquifer*. Paper presented at the SWIM21 - 21st Salt Water Intrusion Meeting, Azores, Portugal.

Liles, M., Thomas, S., & Sovich, T. (2001). *Saltwater intrusion in orange county, california: Planning for the future.* Paper presented at the First International Conference on Saltwater Intrusion and Coastal Aquifers e Monitoring, Modeling, and Management, Essauira, Morocco.

Lin, J., Snodsmith, J. B., Zheng, C., & Wu, J. (2009). A modeling study of seawater intrusion in Alabama Gulf Coast, USA. *Environmental geology, 57*(1), 119-130.

Liu, L. (2002). Saline Water Intrusion. *Natural and Human Induced Hazards, Volume ii*.

Liu, P. L., Cheng, A. H., Liggett, J. A., & Lee, J. H. (1981). Boundary integral equation solutions to moving interface between two fluids in porous media. *Water Resources Research, 17*(5), 1445-1452.

Liu, W.-C., Chen, W.-B., & Hsu, M.-H. (2011). Influences of Discharge Reductions on Salt Water Intrusion and Residual Circulation in Danshuei River. *Journal of Marine Science and Technology, 19*(6), 596-606.

Liu, Y., Shang, S.-H., & Mao, X.-M. (2012). Tidal effects on groundwater dynamics in coastal aquifer under different beach slopes. *Journal of Hydrodynamics, Ser. B, 24*(1), 97-106.

López-Ramírez, J. A., Oviedo, M., & Alonso, J. (2006). Comparative studies of reverse osmosis membranes for wastewater reclamation. *Desalination, 191*(1), 137-147.

Lu, C. (2011). *Mixing in complex coastal hydrogeologic systems.* Doctor of Philosophy in the School of Civil and Environmental Engineering, Georgia Institute of Technology.

Lu, C., Werner, A. D., Simmons, C. T., Robinson, N. I., & Luo, J. (2012). Maximizing Net Extraction Using an Injection-Extraction Well Pair in a Coastal Aquifer. *Ground Water*.

Luckey, R., Gutentag, E., Heimes, F., & Weeks, J. (1986). Digital simulation of groundwater flow in the High Plains aquifer in the parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming. USGS Professional Paper 1400-D. US Geological Survey, Washington, DC, USA, p. 57.

Luyun, J. R., Momii, K., & Nakagawa, K. (2009). Laboratory-scale saltwater behavior due to subsurface cutoff wall. *Journal of Hydrology, 377*(3), 227-236.

Luyun, R., Momii, K., & Nakagawa, K. (2011). Effects of recharge wells and flow barriers on seawater intrusion. *Ground Water, 49*(2), 239-249.

Ma, F., Yang, Y., Cai, Z., Chen, M., & Yuan, R. (2005). Dynamic process analyses of saline intrusion with over-exploitation by coupled flow and dispersive modelling. *Environmental geology, 48*(6), 818-828.

Ma, T. S., Sophocleous, M., Yu, Y.-S., & Buddemeier, R. (1997). Modeling saltwater upconing in a freshwater aquifer in south-central Kansas. *Journal of Hydrology, 201*(1), 120-137.

Maas, K. (2007). Influence of climate change on a Ghijben–Herzberg lens. *Journal of Hydrology, 347*(1), 223-228.

Mahesha, A. (1996a). Control of seawater intrusion through injection-extraction well system. *Journal of irrigation and drainage engineering, 122*(5), 314-317.

Mahesha, A. (1996b). Steady-state effect of freshwater injection on seawater intrusion. *Journal of irrigation and drainage engineering, 122*(3), 149-154.

Mahesha, A. (1996c). Transient effect of battery of injection wells on seawater intrusion. *Journal of Hydraulic Engineering, 122*(5), 266-271.

Mahesha, A., & Nagaraja, S. (1995). Effect of surface source variation on seawater intrusion in aquifers. *Journal of irrigation and drainage engineering, 121*(1), 109-113.

Maimone, M. (2001). *Computer modelling and surface geophysics unravel the mystery of salt water intrusion in Long Isalnd.* Paper presented at the Proceeding of the 1st international conference and workshop on saltwater intrusion and coastal aquifers, monitoring, modelling, and management, Morocco.

Maimone, M., & Fitzgerald, R. (2001). *Effective modelling of coastal aquifers systems.* Paper presented at the Proceeding of the 1st international conference and workshop on saltwater intrusion and coastal aquifers, monitoring, modelling, and management, (Morocco).

Maliva, R., & Missimer, T. (2012). *Arid lands water evaluation and management*: Springer.

Mandle, R. J. (2002). Groundwater modeling guidance. *Groundwater Modeling Program, Michigan Department of Environmental Quality*.

Mantoglou, A., & Papantoniou, M. (2008). Optimal design of pumping networks in coastal aquifers using sharp interface models. *Journal of Hydrology, 361*(1), 52-63.

Mao, X., Enot, P., Barry, D., Li, L., Binley, A., & Jeng, D.-S. (2006). Tidal influence on behaviour of a coastal aquifer adjacent to a low-relief estuary. *Journal of Hydrology, 327*(1), 110-127.

Marksamer, A. J., Person, M. A., Day-Lewis, F. D., Lane, J. W., Cohen, D., Dugan, B., . . . Willett, M. (2007). *Integrating geophysical, hydrochemical, and hydrologic data to understand the freshwater resources on Nantucket Island, Massachusetts*: Wiley Online Library.

Martínez, M. I., Troester, J. W., & Richards, R. T. (1995). Surface electromagnetic geophysical exploration of the ground-water resources of Isla de Mona, Puerto Rico, a Caribbean carbonate island. *Carbonates and Evaporites, 10*(2), 184-192.

McDonald, M. G., & Harbaugh, A. W. (1998). *A Modular Three-dimensional Finite-difference Ground-water Flow Model: Book 6, Chapter A1*: USGS Techniques of Water-Resources Investigations.

Melloul, A., & Goldenberg, L. (1997). Monitoring of seawater intrusion in coastal aquifers: basics and local concerns. *Journal of environmental management, 51*(1), 73-86.

Mercer, J. W., Larson, S., & Faust, C. R. (1980). Finite-difference model to simulate the areal flow of salt water and fresh water separated by an interface. *U.S. Geol. Surv., Open-File Rep. 80--407, 88 pp.*

Metzger, L. F., & Izbicki, J. A. (2013). Electromagnetic-Induction Logging to Monitor Changing Chloride Concentrations. *Ground Water, 51*(1), 108-121.

Mohammed, T. A., & Huat, B. B. (2004). *Groundwater Engineering and Geotechnique*: Universiti Putra Malaysia Press.

Mukhopadhyay, A., Al-Awadi, E., Oskui, R., Hadi, K., Al-Ruwaih, F., Turner, M., & Akber, A. (2004). Laboratory investigations of compatibility of the Kuwait Group aquifer, Kuwait, with possible injection waters. *Journal of Hydrology, 285*(1), 158-176.

Mulrennan, M., & Woodroffe, C. (1998). Saltwater intrusion into the coastal plains of the Lower Mary River, Northern Territory, Australia. *Journal of environmental management, 54*(3), 169-188.

Narayan, K. A., Schleeberger, C., & Bristow, K. L. (2007). Modelling seawater intrusion in the Burdekin Delta irrigation area, North Queensland, Australia. *Agricultural water management, 89*(3), 217-228.

Nienhuis, p., Kamps, P., Spillekom, S., & Olsthoorn, T. (2010). *Comparing methods for exploring the fresh/salt groundwater interface position in the Amsterdam water supply dunes.* Paper presented at the Proceedings of SWIM 21 - 21st Salt Water Intrusion Meeting, Azores, Portugal.

Nishikawa, T., Siade, A., Reichard, E., Ponti, D., Canales, A., & Johnson, T. (2009). Stratigraphic controls on seawater intrusion and implications for groundwater

management, Dominguez Gap area of Los Angeles, California, USA. *Hydrogeology Journal, 17*(7), 1699-1725.

Noorazuan, M., Ruslan, R., Hafizan, J., Sharifuddin, M., & Nazari, J. (2003). *GIS Application In Evaluating Land UseLand Cover Change and its Impact on Hydrological Regime in Langat River Basin, Malaysia.* Paper presented at the Map Asia Conference, Malaysia.

Nowroozi, A. A., Horrocks, S. B., & Henderson, P. (1999). Saltwater intrusion into the freshwater aquifer in the eastern shore of Virginia: a reconnaissance electrical resistivity survey. *Journal of Applied Geophysics, 42*(1), 1-22.

Ogilvy, R., Meldrum, P., Kuras, O., Wilkinson, P., Chambers, J., Sen, M., . . . Frances, I. (2009). Automated monitoring of coastal aquifers with electrical resistivity tomography. *Near Surface Geophysics, 7*(5-6), 367-375.

Ojeda, C. G., Gallardo, P., Hita, L. G., & Arteaga, L. M. (2004). *Saline interface of the Yucatan peninsula aquifer.* Paper presented at the Proceeding of the 18th Salt Water Intrusion Meeting, Cartagena (Spain).

Ong, J. B., Lane Jr, J. W., Zlotnik, V. A., Halihan, T., & White, E. A. (2010). Combined use of frequency-domain electromagnetic and electrical resistivity surveys to delineate near-lake groundwater flow in the semi-arid Nebraska Sand Hills, USA. *Hydrogeology Journal, 18*(6), 1539-1545.

Ortuño, F., Molinero, J., Custodio, E., Juárez, I., Garrido, T., & Fraile, J. (2010). *Seawater intrusion barrier in the deltaic Llobregat aquifer (Barcelona, Spain): performance and pilot phase results.* Paper presented at the SWIM21–21st Salt water intrusion meeting, Azores, Portugal.

Oteri, A. U. (1988). Electric log interpretation for the evaluation of salt water intrusion in the eastern Niger Delta. *Hydrological sciences journal, 33*(1), 19-30.

Paine, J. G. (2003). Determining salinization extent, identifying salinity sources, and estimating chloride mass using surface, borehole, and airborne electromagnetic induction methods. *Water Resources Research, 39*(3).

Paniconi, C., Khlaifi, I., Lecca, G., Giacomelli, A., & Tarhouni, J. (2001). Modeling and analysis of seawater intrusion in the coastal aquifer of eastern Cap-Bon, Tunisia. *Transport in porous media, 43*(1), 3-28.

Panigrahi, B., Gupta, A. D., & Arbhabhirama, A. (1980). Approximation for Salt-Water Intrusion in Unconfined Coastal Aquifer. *Ground Water, 18*(2), 147-151.

Park, N., Huyakorn, Y., Wu, & Barcelo, M. (1993). *sharp interface saltwater intrusion code for layered aquifer system.* Paper presented at the proceeding of symposium on engineering hydrology

Paster, A., & Dagan, G. (2008a). Mixing at the interface between fresh and salt waters in 3D steady flow with application to a pumping well in a coastal aquifer. *Advances in water resources, 31*(12), 1565-1577.

Paster, A., & Dagan, G. (2008b). Mixing at the interface between two fluids in aquifer well upconing steady flow. *Water Resources Research, 44*(5), W05408.

Petalas, C., Pliakas, F., Kallioras, A., & Diamantis, I. (2002). *Engineering, managerial and economical elements of recent trends for the prevention of seawater intrusion in coastal aquifers.* Paper presented at the Proceedings of 6th hydrogeological conference of the Greek Hydrogeological Committee of the Geological Society of Greece, Xanthi, Greece.

Pina, A. L., Gomes, A. M., Melo, M. T. C., & Silva, M. A. M. (2004). *The impact of saltwater intrusion on groundwater quality and the social and economical development of the Santiago island (Cape Verde).* Paper presented at the the 18th Salt Water Intrusion Meeting, Cartagena, spain.

Pinder, G. F., & Celia, M. A. (2006). *Subsurface hydrology*: Wiley Online Library.

Pinder, G. F., & Cooper, H. H. (1970). A numerical technique for calculating the transient position of the saltwater front. *Water Resources Research, 6*(3), 875-882.

Pinder, G. F., & Frind, E. O. (1972). Application of Galerkin's procedure to aquifer analysis. *Water Resources Research, 8*(1), 108-120.

Polemio, M., Dragone, V., & Limoni, P. (2006). *Salt contamination of Apulian aquifers: Spatial and time trend.* Paper presented at the 1st SWIM-SWICA meeting (19th SWIM & 3rd SWICA jointed meeting).

Pool, M., & Carrera, J. (2010). Dynamics of negative hydraulic barriers to prevent seawater intrusion. *Hydrogeology Journal, 18*(1), 95-105.

Pool, M., & Carrera, J. (2011). A correction factor to account for mixing in Ghyben-Herzberg and critical pumping rate approximations of seawater intrusion in coastal aquifers. *Water Resources Research, 47*(5).

Post, V. (2005). Fresh and saline groundwater interaction in coastal aquifers: Is our technology ready for the problems ahead? *Hydrogeology Journal, 13*(1), 120-123.

Poulsen, S. E., Rasmussen, K. R., Christensen, N. B., & Christensen, S. (2010). Evaluating the salinity distribution of a shallow coastal aquifer by vertical multielectrode profiling (Denmark). *Hydrogeology Journal, 18*(1), 161-171.

Praveena, S. M., Abdullah, M., & Aris, Z. (2010). Modeling for equitable groundwater management. *International Journal of Environmental Research, 4*(3), 415-426.

Praveena, S. M., Abdullah, M. H., Bidin, K., & Aris, A. Z. (2012). Sustainable groundwater management on the small island of Manukan, Malaysia. *Environmental Earth Sciences, 66*(3), 719-728.

Praveena, S. M., & Aris, A. Z. (2010). Groundwater resources assessment using numerical model: a case study in low-lying coastal area. *Int J Environ Sci Technol, 7*(1), 135-146.

Putti, M., & Paniconi, C. (1995). Picard and Newton linearization for the coupled model for saltwater intrusion in aquifers. *Advances in water resources, 18*(3), 159-170.

Qahman, K. (2004). *Aspects of hydrology, modeling, and management of saltwater intrusion for Gaza Aquifer – Palestine.* . PhD thesis, Mohamed V-Agdal University.

Qahman, K., & Larabi, A. (2006). Evaluation and numerical modeling of seawater intrusion in the Gaza aquifer (Palestine). *Hydrogeology Journal, 14*(5), 713-728.

Qurtobi, M., Bouchaou, L., IbnMajah, M., Marah, H., Gaye, C. B., & Michelot, J. L. (2004). *"Origin of salinity and its impact on fresh ground water resources in the Souss-Massa Basin in the South- west of Morocco: optimisation of isotopic techniques".* Paper presented at the Proceeding of the 18th Salt Water Intrusion Meeting, Cartagena (Spain).

Rastogi, A., Choi, G. W., & Ukarande, S. (2004). Diffused Interface Model to Prevent Ingress of Sea Water in Multi-Layer Coastal Aquifers. *Journal of Spatial Hydrology, 4*(2).

Reichard, E. G., & Johnson, T. A. (2005). Assessment of regional management strategies for controlling seawater intrusion. *Journal of water resources planning and management, 131*(4), 280-291.

Reilly, T. E., & Goodman, A. S. (1985). Quantitative analysis of saltwater-freshwater relationships in groundwater systems—A historical perspective. *Journal of Hydrology, 80*(1), 125-160.

Renner, J. F., Kroitoru, L., & Snell, R. (2001). *literature survey of methods to control swi into floridan aquifer.* Paper presented at the Proceeding of The 2001 Georgia Water Resources Confernces, Institute of Ecology, the University of Georgia, Athens, Georgia.

Rittmann, B. E., McCarty, P. L., & Roberts, P. V. (1980). Trace-Organics Biodegradation in Aquifer Recharge. *Ground Water, 18*(3), 236-243.

Ru, Y., Jinno, K., Hosokawa, T., & Nakagawa, K. (2001). *Study on effect of subsurface dam in coastal seawater intrusion.* Paper presented at the 1st Int conf saltwater intrusion and coastal aquifers, monitoring, modelling, and management (Morocco).

R.18

Rumer, R. R., & Shiau, J. (1968). Salt water interface in a layered coastal aquifer. *Water Resources Research, 4*(6), 1235-1247.

Sanford, W. E., & Konikow, L. F. (1985). *A two-constituent solute-transport model for ground water having variable density*: US Geological Survey.

Satriani, A., Loperte, A., Imbrenda, V., & Lapenna, V. (2012). Geoelectrical Surveys for Characterization of the Coastal Saltwater Intrusion in Metapontum Forest Reserve (Southern Italy). *International Journal of Geophysics, 2012*.

Scholze, O., Schneider, W., Hillmer, G., Schulz, H., & Hadeler, A. (2003). *Protection of the groundwater resources of Metropolis Cebu (Philippines) in consideration of saltwater intrusion into the coastal aquifer.* Paper presented at the Geochemical processes in soil and groundwater: measurement, modelling, upscaling. GeoProc2002 conference, Bremen, Germany, 4-7 March 2002.

Schotting, R., Moser, H., & Hassanizadeh, S. (1999). High-concentration-gradient dispersion in porous media: experiments, analysis and approximations. *Advances in water resources, 22*(7), 665-680.

Schroeder, D. J., Harley, B. M., & Mejia, P. E. C. (1989). Seawater intrusion barrier elevated with 3-D ground water models. *Water Engrg. and Mgmt., 136*(2), 26-29.

Segol, G. (1994). Classic groundwater simulations: proving and improving numerical models.

Segol, G., & Pinder, G. F. (1976). Transient simulation of saltwater intrusion in southeastern Florida. *Water Resources Research, 12*(1), 65-70.

Segol, G., Pinder, G. F., & Gray, W. G. (1975). A Galerkin-finite element technique for calculating the transient position of the saltwater front. *Water Resources Research, 11*(2), 343-347.

Shamir, U., & Dagan, G. (1971). Motion of the seawater interface in coastal aquifers: A numerical solution. *Water Resources Research, 7*(3), 644-657.

Shamir, U. Y., & Harleman, D. R. (1967). Numerical solutions for dispersion in porous mediums. *Water Resources Research, 3*(2), 557-581.

Shammas, M., & Jacks, G. (2007). Seawater intrusion in the Salalah plain aquifer, Oman. *Environmental geology, 53*(3), 575-587.

Shammas, M. I. (2008). The effectiveness of artificial recharge in combating seawater intrusion in Salalah coastal aquifer, Oman. *Environmental geology, 55*(1), 191-204.

Sheahan, N. T. (1977). Injection/Extraction Well System–A Unique Seawater Intrusion Barriera. *Ground Water, 15*(1), 32-50.

Sherif, M., & Kacimov, A. (2008). Pumping of brackish and saline water in coastal aquifers: an effective tool for alleviation of seawater intrusion. *Proceeding of 20th SWIM, Naples, Florida, USA.*

Sherif, M., Kacimov, A., Ebraheem, A., & AlMulla, M. (2010). *Three-dimensional mapping of seawater intrusion using geophysical methods.* Paper presented at the World environmental and water resources congress.

Sherif, M., Kacimov, A., Javadi, A., & Ebraheem, A. A. (2012). Modeling groundwater flow and seawater intrusion in the coastal aquifer of Wadi Ham, UAE. *Water resources management, 26*(3), 751-774.

Sherif, M., Sefelnasr, A., & Javadi, A. (2012). *Areal Simulation of Seawater Intrusion in the Nile Delta Aquifer.* Paper presented at the World Environmental and Water Resources Congress 2012@ sCrossing Boundaries.(pp. 22-28).ASCE.

Sherif, M. M., & Hamza, K. I. (2001). Mitigation of seawater intrusion by pumping brackish water. *Transport in porous media, 43*(1), 29-44.

Siemon, B., Christiansen, A. V., & Auken, E. (2009). A review of helicopter-borne electromagnetic methods for groundwater exploration. *Near Surface Geophysics, 7*(5-6), 629-646.

Siemon, B., Steuer, A., Seht, M. I.-v., Voß, W., Meyer, U., & Wiederhold, H. (2012). *Combination of Airborne Geophysical Surveys at the Estuaries of the Weser and Elbe Rivers in Northern Germany.* Paper presented at the Remote Sensing 2012.

Simmons, C. T. (2005). Variable density groundwater flow: From current challenges to future possibilities. *Hydrogeology Journal, 13*(1), 116-119.

Simpson, M., & Clement, T. (2003). Theoretical analysis of the worthiness of Henry and Elder problems as benchmarks of density-dependent groundwater flow models. *Advances in water resources, 26*(1), 17-31.

Simpson, M. J., & Clement, T. P. (2004). Improving the worthiness of the Henry problem as a benchmark for density-dependent groundwater flow models. *Water Resources Research, 40*(1).

Simpsonie, M., & Clement, T. (2005). Testing numerical models of variable density ground water flow: Current trends and the renaissance of the Henry problem. *Groundwater and saline intrusion*(15), 41.

Sindhu, G., Ashith, M., Jairaj, P., & Raghunath, R. (2012). Modelling of Coastal Aquifers of Trivandrum. *Procedia Engineering, 38*, 3434-3448.

Smith, A. J., & Turner, J. V. (2001). Density-dependent surface water–groundwater interaction and nutrient discharge in the Swan–Canning Estuary. *Hydrological Processes, 15*(13), 2595-2616.

Sorek, S., Borisov, V., & Yakirevich, A. (2001). A two-dimensional areal model for density dependent flow regime. *Transport in porous media, 43*(1), 87-105.

Souza, W. R., & Voss, C. I. (1987). Analysis of an anisotropic coastal aquifer system using variable-density flow and solute transport simulation. *Journal of Hydrology, 92*(1), 17-41.

Srinivasamoorthy, K., Vasanthavigar, M., Chidambaram, S., Anandhan, P., & Sarma, V. (2011). Characterisation of groundwater chemistry in an eastern coastal area of Cuddalore district, Tamil Nadu. *Journal of the Geological Society of India, 78*(6), 549-558.

Stewart, M. (1999). Geophysical investigations. In J. Bear, A. Cheng, S. Sorek, D. Ouazar & I. Herrera (Eds.), *Seawater intrusion in coastal aquifers: concepts, methods and practices*. Dortrecht, The Netherlands: Kluwer.

Stewart, M. T. (1982). Evaluation of electromagnetic methods for rapid mapping of salt-water interfaces in coastal aquifers. *Ground Water, 20*(5), 538-545.

Strack, O. (1976). A single-potential solution for regional interface problems in coastal aquifers. *Water Resources Research, 12*(6), 1165-1174.

Strack, O. D. (1989). *Groundwater mechanics*: Prentice Hall.

Sugio, S., Nakada, K., & Urish, D. W. (1987). Subsurface seawater intrusion barrier analysis. *Journal of Hydraulic Engineering, 113*(6), 767-779.

Suratman, S. (2005). The study on sustainable groundwater resources and environmental management for the Langat Basin in Malaysia. *Groundwater Intensive Use: Selected Papers, SINEX, Valencia, Spain, 10-14 December 2002, 7*, 341.

Swartz, J. (1937). Resistivity-studies of some salt-water boundaries in the Hawaiian Islands. *Transactions, American Geophysical Union, 18*, 387-393.

Taha, M. (2003). *Groundwater and governmental quality issues in the Langat Basin, Malaysia. In Groundwater Engineering – Recent Advances: Proceedings of the International Symposium on Groundwater Problems Related to Geo-environment, Okayama, Japan (Komatsu M, Nishigaki M, Kono I. (Eds)). Taylor & Francis, London, pp.89-97.*

Taigbenu, A. E., Liggett, J. A., & Cheng, A. H. D. (1984). Boundary integral solution to seawater intrusion into coastal aquifers. *Water Resources Research, 20*(8), 1150-1158.

Thomas, S. D., Liles, J. M., & Johnson, T. A. (2001). *Managing seawater intrusion in the Dominguez gap area of Los Angeles country, California, USA*. Paper presented at the 1st international conference and workshop on saltwater intrusion and coastal aquifers, monitoring, modelling, and management Morocco.

Ting, C. S., Zhou, Y., Vries, J. d., & Simmers, I. (1998). Development of a preliminary ground water flow model for water resources management in the Pingtung Plain, Taiwan. *Ground Water, 36*(1), 20-36.

Todd, D. K. (1974). Salt-water intrusion and its control. *Journal American Water Works Association, 66*(3), 180 - 187.

Todd, D. K., & Mays, L. W. (1980). Groundwater Hydrology Edition.

Todd, D. K., & Mays, L. W. (2005). Groundwater hydrology: John Wiley & Sons, USA.

Tompson, A., Davisson, M., Maxwell, R., Hudson, G., Welty, C., Carle, S., & Rosenberg, N. (2001). *On the fate of artificial recharge in a coastal aquifer, .* Paper presented at the Proceeding of the 1st international conference and workshop on saltwater intrusion and coastal aquifers, monitoring, modelling, and management., (Morocco).

Tulipano, L., & Fidelibus, M. (2002). Mechanism of groundwater salinisation in a coastal karstic aquifer subject to over-exploitation. *Proceedings of 17th SWIM, Delft, The Netherlands*.

Umar, H., Dayang Suraya, S., & Nazihah, M. (2006). Mapping of Aquifer by Geoelectrical Techniques at Sungai Kelambu, Banting, Selangor, Malaysia. *Sains Malaysiana, 35*(2), 35-40.

Urish, D. W., & Frohlich, R. K. (1990). Surface electrical resistivity in coastal groundwater exploration. *Geoexploration, 26*(4), 267-289.

USACE. (2001). Final groundwater model calibration report, Aquifer storage and recovery, Regional modeling study. February 2011.

Van Dam, J., & Meulenkamp, J. (1967). Some results of the geo-electrical resistivity method in ground water investigations in the Netherlands. *Geophysical prospecting, 15*(1), 92-115.

Van Duijn, C., Peletier, L., & Schotting, R. (1998). Brine transport in porous media: self-similar solutions. *Advances in water resources, 22*(3), 285-297.

Vandenbohede, A., & Lebbe, L. (2003). Combined interpretation of pumping and tracer tests: theoretical considerations and illustration with a field test. *Journal of Hydrology, 277*(1), 134-149.

Vandenbohede, A., & Lebbe, L. (2006). Occurrence of salt water above fresh water in dynamic equilibrium in a coastal groundwater flow system near De Panne, Belgium. *Hydrogeology Journal, 14*(4), 462-472.

Vandenbohede, A., & Lebbe, L. (2007). Effects of tides on a sloping shore: groundwater dynamics and propagation of the tidal wave. *Hydrogeology Journal, 15*(4), 645-658.

Vandenbohede, A., & Lebbe, L. (2011). Heat transport in a coastal groundwater flow system near De Panne, Belgium. *Hydrogeology Journal, 19*(6), 1225-1238.

Vandenbohede, A., Lebbe, L., Adams, R., Cosyns, E., Durinck, P., & Zwaenepoel, A. (2010). Hydrogeological study for improved nature restoration in dune ecosystems–Kleyne Vlakte case study, Belgium. *Journal of environmental management, 91*(11), 2385-2395.

Vandenbohede, A., Lebbe, L., Gysens, S., Delecluyse, K., & DeWolf, P. (2008). Salt water infiltration in two artificial sea inlets in the Belgian dune area. *Journal of Hydrology, 360*(1), 77-86.

Vandenbohede, A., Luyten, K., & Lebbe, L. (2008). Effects of global change on heterogeneous coastal aquifers: a case study in Belgium. *Journal of Coastal Research, 24*(sp2), 160-170.

Vandenbohede, A., Van Houtte, E., & Lebbe, L. (2008). Groundwater flow in the vicinity of two artificial recharge ponds in the Belgian coastal dunes. *Hydrogeology Journal, 16*(8), 1669-1681.

Vandenbohede, A., Van Houtte, E., & Lebbe, L. (2009). Sustainable groundwater extraction in coastal areas: a Belgian example. *Environmental geology, 57*(4), 735-747.

Viezzoli, A., Tosi, L., Teatini, P., & Silvestri, S. (2010). Surface water–groundwater exchange in transitional coastal environments by airborne electromagnetics: the Venice Lagoon example. *Geophysical Research Letters, 37*(1).

Voss, C. I. (1984). *A finite-element simulation model for saturated-unsaturated, fluid-density-dependent ground-water flow with energy transport or chemically-reactive single-species solute transport* (Vol. 84): US Geological Survey.

Voss, C. I., & Provost, A. (2002). SUTRA, a model for saturated-unsatu- rated variable-density ground-water flow with solute or energy transport,. In U. S. G. S. W. Resour (Ed.), *Water Resour. Invest. Rep* (pp. 02-4231).

Voss, C. I., Simmons, C. T., & Robinson, N. I. (2010). Three-dimensional benchmark for variable-density flow and transport simulation: matching semi-analytic stability modes for steady unstable convection in an inclined porous box. *Hydrogeology Journal, 18*(1), 5-23.

Voss, C. I., & Souza, W. R. (1987). Variable density flow and solute transport simulation of regional aquifers containing a narrow freshwater-saltwater transition zone. *Water Resources Research, 23*(10), 1851-1866.

Wang, H. F., & Anderson, M. P. (1995). *Introduction to groundwater modeling: finite difference and finite element methods*: Academic Press.

Ward, D. S. (1991). Data Input for SWIFT/386, version 2.50, Geotrans Technical Report, Sterling, Va.

Ward, D. S., & Benegar, J. (1998). Data Input Guide for SWIFT-98, version 2.57, HSI Geotrans, Inc., Sterling, Va.

Watson, T. A., Werner, A. D., & Simmons, C. T. (2010). Transience of seawater intrusion in response to sea level rise. *Water Resources Research, 46*(12).

Webb, M. D., & Howard, K. W. (2011). Modeling the Transient Response of Saline Intrusion to Rising Sea-Levels. *Ground Water, 49*(4), 560-569.

Werner, A. D., Bakker, M., Post, V. E., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., . . . Barry, D. A. (2013). Seawater intrusion processes, investigation and management: Recent advances and future challenges. *Advances in water resources, 51*, 3-26.

Werner, A. D., Bakker, M., Post, V. E. A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., . . . Barry, D. A. (2012). Seawater intrusion processes, investigation and management: Recent advances and future challenges. *Advances in water resources*.

Willert, T., Behain, D., Fulda, C., Worzyk, P., & Kessels, W. (2001). Regional saltwater distribution in the Coastal Aquifer Test Field (CAT-Field) between Bremerhaven and Cuxhaven, Germany, by DC-geoelectric measurements. *Proc. SWICA-M³, Essaouira, Morocco*.

Wilson, J. L., & Sa Da Costa, A. (1982). Finite element simulation of a saltwater/freshwater interface with indirect toe tracking. *Water Resources Research, 18*(4), 1069-1080.

WMO. (1988). Manual on water-quality monitoring. In W. M. O. O. H. Report (Ed.), *W.M.O. Operational Hydrology Report* (Vol. 27, pp. 197).

Woods, J. A. (2004). *Numerical Accuracy of Variable-Density Groundwater Flow and Solute Transport Simulations.* Doctor of Philosophy in Applied Mathematics, University of Adelaide.

Yager, R. M. (1987). Simulation of ground-water flow near the nuclear-fuel reprocessing facility at the Western New York Nuclear Service Center, Cattaraugus County, New York, Cattaraugus County, New York. USGS Water Resources Investigation Report 85–4308, pp 58.

Yechieli, Y., Shalev, E., Wollman, S., Kiro, Y., & Kafri, U. (2010). Response of the Mediterranean and Dead Sea coastal aquifers to sea level variations. *Water Resources Research, 46*(12).

Zaporozec, A. (2002). Groundwater contamination inventory: A methodological guide. *IHP-VI, Series on groundwater, 2*.

Zhang, H., Baray, D., & Hocking, G. (1999). Analysis of continuous and pulsed pumping of a phreatic aquifer. *Advances in water resources, 22*(6), 623-632.

Zheng, C. (1999). MT3D99 A modular 3D multispecies transport simulator, SS Papadopulos and Associates. *Inc. Bethesda, Maryland*.

Zheng, C., & Bennett, G. (2002). *Applied Contaminant Transport Modeling Second Edition, Wiley, New York, 621 pp.*

Zheng, C., & Wang, P. P. (1999). MT3DMS: A modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems; documentation and user's guide: DTIC Document.

Zohdy, A. A., & Jackson, D. B. (1969). Application of deep electrical soundings for groundwater exploration in Hawaii. *Geophysics, 34*(4), 584-600.