UNIVERSITI PUTRA MALAYSIA

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

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Thesis submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfillment of the Requirements for the Degree of
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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

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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.
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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.

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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:

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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.

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