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SIMULATION AND CONTROL OF SALTWATER INTRUSION THROUGH NUMERICAL AND PHYSICAL MODELING TECHNIQUES

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By

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Abstract of dissertation presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Doctor of Philosophy.

SIMULATION AND CONTROL OF SALTWATER INTRUSION THROUGH NUMERICAL AND PHYSICAL MODELING TECHIQUES

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Faculty: Engineering

Simulation and control of saltwater intrusion based on hydrodynamic dispersion has been investigated through numerical and physical modeling techniques. In the mathematical formulation, two equations were derived one for water flow and the other for solute transport that were coupled through Darcy's velocity and concentration. In the numerical model formulation, Galerkin finite element approach was applied for deriving the element matrix equation through quadrilateral elements. To save memory and computation time, a pointer matrix was used to avoid storage of most of the zeros in the resulting sparse matrix. The developed model was an efficient and a rather general one such that the aquifer can be of any types with different boundary conditions and unlimited number of sources and sinks. For model verification, Henry's problem was used to compare the model results with previous studies that applied constant and velocity-dependent dispersion coefficient. The comparison showed a good agreement

between the proposed model and the previous ones. Also, for simulation of saltwater intrusion the computed isochlor contours for the physical model were in good agreement with the experimental ones

By using the sandbox model and other apparatuses, the average values of porosity, hydraulic conductivity, dispersion coefficient, and saltwater density were found to be 0.36, 0.0855 cm/s, 14.34, 10^{-2} cm^2/s, and 1027.5 kg/m^3 respectively. These parameters were used in the numerical simulation. Saltwater intrusion was simulated experimentally using the physical model under steady and unsteady state conditions through the measurement of the sodium chloride distribution in the aquifer. According to physical simulation, the intruded length was changed from 48 cm at steady state to 79 cm at the end of 90 minutes from the steady state during which the freshwater head was changed every 30 minutes by 0.5 cm from 50 cm to 48.5 cm.

Both models were used to investigate the effect of aquifer recharge and discharge of saltwater from saltwater zone on the intruded length under steady state conditions with freshwater head and saltwater head as 48.5 cm and 47.5 cm respectively. The 0.5 isochlor contour toe was changed from 76 cm away from saltwater reservoir for no recharge to 71 and 70 cm for recharges of 10 and 12 cm^3/sec respectively. For discharge case, it was changed from 76 cm to 72 cm for a discharge of 10 cm^3/sec. Affect of rate and location of the recharge and discharge methods on the intruded length was investigated through the numerical model using a hypothetical anisotropic aquifer, with parameters very closed to reality. As a result of the investigation, the rate in both methods has considerable effect on the intruded length of saltwater intrusion. For example, the intruded length was shifted from 136 m for no recharge to 62 m for a point recharge of 0.06 m/day. Whereas, for discharge the method the intruded length was changed from 136 m to 72 m for a discharge of 4 m^3/day. On the other hand, the location has small effect especially when shifted away from the sea side.

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SIMULASI DAN KAWALAN TERHADAP PENEROBOSAN AIR MASIN MELALUI TEKNIK PEMODELAN FIZIKAL DAN BERANGKA

Oleh

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Kajian berdasarkan penyerakan hidrodinamik telah dijalankan dengan menggunakan teknik model fizikal dan berangka ke atas simulasi dan kawalan penerobosan air masin. Formulasi matematik telah menghasilkan dua persaman iaitu untuk aliran air dan pengaliran larut yang kemudiannya dikembarkan mengikut kelajuan dan kepekatan formula Darcy. Formulasi elemen finit dengan menggunakan kaedah Galerkin telah digunakan untuk menghasilkan persamaan elemen matrik secara quadrilateral. Matrik penunjuk digunakan untuk mengurangkan penggunaan memori dan masa untuk pengiraan dan juga mengelakkan penyimpanan kebanyakkan angka kosong dalam matrik ruang yang terhasil. Model yang terhasil adalah efisyen dan lebih umum untuk diuji pada pelbagai akuifer dalam pelbagai keadaan sempadan serta pelbagai punca dan sink. Permasalahan Henry telah digunakan untuk membandingkan hasil keputusan model dengan kajian awal yang bergantung kepada koefisyen penyerakan sekata dan

halaju. Perbandingan telah menunjukan pertalian yang baik diantara model yang dicadangkan dengan model terdahulu. Pengiraan kontor isochlor untuk model fizikal adalah sebaik hasil eksperimen dalam simulasi penorobosan air masin.

Hasil kajian dari model fizikal yang merupakan model tangki berpasir mendapati nilai purata untuk keliangan, konduktiviti hidraulik, koefisyen penyerakan dan ketumpatan air masin adalah 0.36, 0.0855 cm/s, 14.24×10^{-2} cm^2/s dan 1027.5 kg/m^2. Parameter ini telah digunakan dalam simulasi model berangka. Penyerakan air masin disimulasikan menggunakan model fizikal dibawah keadaan stabil dan tidak stabil melalui pengukuran pengagihan sodium klorida dalam akuifer. Mengikut simulasi fizikal jarak terobos berubah dari 48 cm pada keadaan stabil sehingga 79 cm selepas 90 minit dari keadaan stabil yang mana turus air tawar berubah setiap 30 minit dari 50 cm kepada 48.5 cm.

Kedua–dua model digunakan untuk mengkaji kesan kadar imbuh serta kadar luahan ke zon air masin yang mana jarak terobos didalam keadaan stabil pada turus 48.5 cm air tawar dan 47.5 cm air masin. Jari kontor 0.5 isochlor untuk model fizikal berubah dari takungan air masin daripada 76 cm kepada 71 dan 70 cm masing–masing untuk kadar imbuh 10 dan 12 cm^3/s. Kadar luah 10 cm^3/s telah mengubah jari kontor ke 72 cm . Kesan kadar dan lokasi untuk kaedah kadar luahan dan imbuhan keatas jarak terobos akuifer hipotesis takisotropik dengan meggunakan parameter yang menghampiri realiti telah diuji dengan menggunakan model berangka. Hasil kajian menunjukkan kedua–dua kaedah mempunyai kesan terhadap jarak terobos penorobosan air masin. Sebagai contoh, jarak terobos berubah dari 136 cm bagi tanpa aliran kepada 62 m untuk titik aliran 0.06 m/hari manakala untuk kaedah kadar alir jarak terobos berubah dari 136 cm kepda 72 m untuk kadar alir 4 m^3/hari. Lokasi cuma memberi kesan yand kecil terutama bila dianjak lari dari tepian pantai.

CHAPTER I

INTRODUCTION

General

The term groundwater is usually referred to the water that occurs beneath the ground surface in a saturated zone of a geologic formation known as aquifers and is related to surface waters in rivers and lakes through the hydrologic cycle. It constitutes the largest available source of freshwater. Therefore, a proper development and utilization of this renewable natural resource are of interest for all water supply requirements. In any evaluation of groundwater resources, physical chemical, and biological characteristics of the water are of major importance in determining whether or not water is suitable for domestic, industrial, or agriculture use.

With increasing demand for water and with the intensification of water utilization, the quality problem becomes the limiting factor in the development of water resources, especially in coastal areas where the population is more condensed. Generally, groundwater contamination is traced back to environmental, agricultural, and domestic and industrial sources. Environmental that is a contamination due to environment through which the flow of groundwater takes place. Seawater intrusion is an example of this pollution. Agricultural that is a pollution due to irrigation and rain water dissolving and carrying fertilizers and salts as they infiltrate through the ground surface. Domestic and industrial contamination that is caused by many ways such as percolation from septic tanks and artificial recharge of aquifers by sewage water. The scope of this study is concerned with the environmental pollution that is caused by the saltwater intrusion.

In coastal aquifers that have their boundaries in contact with saltwater bodies the fresh water is usually, under natural conditions, discharged into the ocean or at sea ward of the coastline. Because of sea water existence in the aquifer formations beneath the sea bottom, a zone of contact is formed between the lighter fresh water that flowing to the sea and the denser underlying sea water. A balance or equilibrium tends to become established between the fresh water and the salt water pressing in from the sea under natural undisturbed conditions in the coastal aquifer with a stationary interface and fresh water flow to the sea above it. When the water table (unconfined aquifer) or the piezometeric head (confined aquifer) in the fresh water body becomes slightly above or less than the head in the adjacent seawater wedge, the interface starts to advance inland. This phenomenon is known as seawater intrusion. Almost, the same phenomenon can be found in most oceanic islands where fresh water forms a lens overlying the sea water. The extent of intrusion depends upon the climatic conditions, the characteristics of the natural flow within these aquifers, and the manner of groundwater usage.

Seawater intrusion represents displacement of miscible liquids in porous media since diffusion and hydrodynamic dispersion tends to mix the two fluids. Therefore, the interfacial surface becomes a transition zone with a variable concentration from fresh water at the top to seawater at the bottom. The thickness of the zone is highly variable; in steady flow the thickness is minimum, while unsteady flows such as pumping, recharge, and tide increases the thickness. Flow in the transition zone varies from that of fresh water at the upper surface to nearly zero at the lower surface. The movement in the transition zone transports the salt, that dispersing upward into the zone from the underlying seawater, to the sea. This flow tends to lessen the extent to which the saltwater occupies the aquifer.

Because of the deterioration of water quality, saltwater intrusion restricts the agricultural, industrial, and domestic use of groundwater from the invaded aquifers. Therefore, an assessment and control of saltwater intrusion in specific coastal area are needed before initiating a major groundwater development program. This can be achieved with proper management, considering the geological and hydrological conditions of the study area.

Management of groundwater system means making various decisions aimed at modifying the state of a considered system to achieve certain goals and objectives without violating specified constraints. Some examples of decision variables are pumpage distribution, quality of pumped water, and distribution and quality of artificial recharge. Examples of the state variables are water levels, concentration of specified species, and seawater intrusion. Some examples of objective functions are maximizing the total net benefits during specified period of time, minimizing the cost of a unit volume of water supplied to the consumer, and minimizing the total consumption of energy. Examples of constraints are water levels that should not drop or rise specified minimum or maximum elevations, the concentrations of a certain species in pumping should not exceed specified threshold values, and the length of an intruding seawater wedge should not exceed specified value. To predict the outcome of implementing management decisions, a tool is required to forecast the aquifer's response to planned operations. The necessary information about the response of the system is provided by a model that describes the behavior of the groundwater system in response to some action. The model may be defined as a simplified version of the real system that approximately simulates the excitation response of the system. The simplification is introduced in the form of a set of assumptions that express the understanding of the nature of the system and its behavior.

Models that have been used in saltwater intrusion simulation can be classified as physical models, viscous analog, electric analogs, and numerical models. The physical model or sand box model is a reduced scale representation of the natural porous medium domain. Since both the prototype and the model involve flow through porous media, the sand box model is considered a true model. Because of its special features that permit studies of phenomena to the microscopic structure of the medium, it has been used extensively in groundwater investigations such as miscible and immiscible displacement and hydrodynamic dispersion. The drawback of this model is presence of the trapped air in the voids and the effect of capillary fringe in case of phreatic aquifer.

The viscous flow analog or Hele-Shaw analog has been used extensively by many investigators for solving regional groundwater flow problems such as seawater intrusion and artificial recharge. The analogy is based on the similarity between the differential equations governing the saturated flow in a porous medium and those describing the flow of a viscous liquid in a narrow space between two parallel plates. In spite of the wide application, there are some factors that limit the model applications such as the effect of changes in temperature during the test, the flow measurement poses some problems, and sometimes over simplification are made to meet certain simulations. In addition, there are some situations where the model could not be used, for example, simulation of the hydrodynamic dispersion and simultaneous flow of two immiscible fluids.

The electric analogs that include electrolytic tank, RC networks, and ion motion are considered very powerful tools in studies involving flow in aquifers. The analogy is based on the similarity between the differential equations that govern the flow of a homogeneous fluid through a porous medium and those governing the flow of electricity through a conducting material. However, because of their analogy, their implementations for groundwater simulations are limited to certain situations. For instance, they could not be used to investigate simulation of phreatic aquifer, hydrodynamic dispersion, observations of streamlines and path lines, and simultaneous flow of two immiscible fluids.

Beside the physical models, various studies have been conducted based on analytical solutions of the governing equations, to study the interaction between freshwater and saltwater. These solutions are simple and take less time in computation. However, because of heterogeneity, irregular geometry, and boundary conditions, the analytical solutions may be impossible for most practical problems unless some drastic simplification assumptions are made. Therefore, only numerical models can provide the required forecast in saltwater intrusion simulations.

Generally, there are some factors such as the complexity of the geology, the manner groundwater flow, and the required applications of the results that control the classification of the numerical models. According to these factors numerical models can be classified as one-, two-, and three-dimensional models. Three-dimensional model is necessary where the geology is complex and the groundwater flow is considered important in all directions. However, its development is limited due to the requirement of large core storage and the complicated calculations involved. Therefore, most of three-dimensional flow models are multilayered models that mean the flow equations that govern the phenomena are actually one- or two-dimensional.

Commonly, the major numerical methods that have been used for modeling groundwater flow and solute transport are finite difference method(FDM), finite element method(FEM), method of characteristics(MOC), and boundary element method(BEM). Each of these methods is based on certain approach and has some advantages and disadvantages. The FDM is simple in concept, easy in programming, and simple in data input. On the other hand, it is difficult to handle problems of irregular boundaries, irregular forms of sources and sinks, and irregular aquifer materials. The FEM is a very powerful and flexible method. It can handle any shape and any combination of boundary conditions. Also, it is more accurate than FDM if the same type and size of mesh are used. The drawback of this method is the difficulty in concept, programming, and data input. However; once the computer programs are developed, it can be easily adopted from one problem to another.

MOC is effective in dealing with the hyperbolic type of partial differential equations. It is widely used for simulating the transport of miscible compounds in groundwater, especially in one- and two-dimensional flow problems. BEM is effective in dealing with elliptic type of partial differential equations such as steady state flow. Both methods have difficulty to handle three-dimensional flow problems and they usually employed in homogeneous and isotropic aquifers.

Applying any of these numerical methods usually yields a set of linear or nonlinear algebraic equations. The solution procedure is either direct or iterative. Each one has advantages and disadvantages. In direct procedure initial estimates of the unknown variables, iteration parameters, and selections of error tolerance are not needed. Also, the matrix operations are performed only once. However, serious round-off errors may occur and it may take more computer storage. The iterative procedure saves computer storage and increases computation accuracy. On the other hand, the solution depends on the initial estimation of unknown variables, the choices of the iteration parameters, and the choices of the error tolerance values.