UNIVERSITI PUTRA MALAYSIA

GROUNDWATER UTILIZATION FROM DENSITY-STRATIFIED NON-HOMOGENEOUS UNCONFINED AQUIFERS

JONG TZE YONG

GROUNDWATER UTILIZATION FROM DENSITY-STRATIFIED NON-HOMOGENEOUS UNCONFINED AQUIFERS

JONG TZE YONG

MASTER OF SCIENCE
UNIVERSITI PUTRA MALAYSIA

2000

GROUNDWATER UTILIZATION FROM DENSITY-STRATIFIED NON-HOMOGENEOUS UNCONFINED AQUIFERS

By

JONG TZE YONG

Thesis Submitted in Fulfilment of the Requirements for the Degree of Master of Science in the Faculty of Engineering Universiti Putra Malaysia

March 2000

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Master of Science.

GROUNDWATER UTILIZATION FROM DENSITY-STRATIFIED NON-HOMOGENEOUS UNCONFINED AQUIFERS

By

JONG TZE YONG

March 2000

Chairman: Abdul Halim Ghazali, M.Sc.

Faculty: Engineering

This investigation concerns the establishing of theoretical framework of a numerical model which governs the selective withdrawal from a density-stratified groundwater reservoir to meet a certain desired water quality constraint. The general class of groundwater systems consists of a saturated porous medium where the denser saltwater tends to remain separated from the overlying freshwater. Pumping from such a stratified reservoir may result in deliveries of water of undesirable quality resulting from the unsteady mixing which occurs between the salt and freshwater layers. The equations which govern the flow of fluids and mass transport of the pollutant through the stratified groundwater reservoir were developed together with the initial and boundary conditions. The flow and solute equations were then solved by using SUTRA model that employs Galerkin finite element method.

In order to verify the numerical model, an experimental laboratory sand model was constructed to study the selective withdrawal phenomenon. Four experimental tests with different set of values of well penetration depth and

pumping rate were carried out to determine the pressure head and concentration distribution in the aquifer domain. To further verify the numerical model, comparisons were carried out between the numerical solutions of pressure head and concentration distribution and the experimental results, and they showed the maximum difference of 10% and 11% respectively. Good agreement was obtained as a result of these comparisons.

Sensitivity analysis was carried out in order to study the effect of variations of dispersivity coefficients on the concentration distributions. It was found that increasing the dispersivity coefficients would enlarge the mixing zone above the saltwater-freshwater interface, thus caused the saltwater moving further upward to the pumping well. At the same time, a case study was also conducted at Sg. Langat basin to test the applicability of the model to the real field conditions. From the simulation of the test well with the data provided by the Geological Survey Department of Malaysia, it was found that the critical time period where the salinity-polluted water will be pumped towards the well is approximately 92 hour after the start of non-stop pumping with constant discharge rate of 114m^3/hr.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains.

PENGGUNAAN AIRBUMI DARI AKUIFER TAK TERKURUNG YANG BERKETUMPATAN STRATA DAN TAK HOMOGEN

Oleh

JONG TZE YONG

Mac 2000

Pengerusi: **En. Abdul Halim Ghazali**

Fakulti: **Kejuruteraan**

Kajian ini berkenaan dengan pembangunan rangka kerja bagi satu model berangka yang mengawal pengepaman selektif dari takungan airbumi berketumpatan strata untuk memenuhi kekangan kualiti air yang dikehendaki. Sistem airbumi secara umumnya terdiri daripada bahantara yang tepu di mana air masin yang lebih berat akan sentiasa terpisah dan berada di bawah air tawar. Pengepaman daripada takungan yang berstrata ini akan menyebabkan pengeluaran kualiti air tidak dikehendaki yang disebabkan oleh pencampuran tidak mantap di antara lapisan air masin dan air tawar. Persamaan-persamaan yang mengawal pengaliran bendalir dan pengangkutan jisim pencemar melalui takungan airbumi berstrata telah dibentuk bersama dengan keadaan awal dan sempadan. Selepas itu, persamaan-persamaan bendalir dan bahan larut akan diselesaikan dengan menggunakan model SUTRA yang mempraktikkan keadah unsur terhingga Galerkin.

Bagi tujuan pengesahan model berangka, satu model berpasir di makmal telah dibina untuk mengkaji fenomena pengeluaran selektif itu. Empat ujian

eksperimen untuk nilai kedalaman penusukan kolam dan kadar pengepaman yang berlainan telah dijalankan untuk menentukan taburan turus tekanan dan kepekatan di dalam domain akuifer. Untuk terus mengesahkan model berangka, perbandingan telah dijalankan di antara penyelesaian berangka bagi taburan turus tekanan dan kepekatan dengan keputusan eksperimen, dan perbezaan maksimum yang didapati adalah sebanyak 10% dan 11% masing-masing. Persetujuan yang baik telah dicapai daripada perbandingan-perbandingan tersebut.

Analisis kepekaan telah dijalankan untuk mengkaji kesan perubahan pekali serakan terhadap taburan kepekatan. Didapati bahawa pertambahan pekali serakan akan memperluaskan zon pencampuran yang berada di bahagain atas sempadan air masin dan air tawar, dan seterusnya menyebabkan air masin bergerak naik ke telaga pengepaman. Pada masa yang sama, satu kes kajian telah dijalankan di Lembah Sg. Langat untuk menguji keberkesanan model berangka terhadap keadaan sebenar. Dari simulasi telaga ujian dengan data yang diperolehi daripada Jabatan Kajibumi Malaysia, didapati tempoh masa kritikal yang mana air yang dicemari kemasinan akan dipam masuk ke telaga adalah lebih kurang 92 jam selepas bermulanya pengepaman tak terhenti pada kadar 114m^3/jam.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my supervisor Mr. Abdul Halim Ghazali for his distinguished advice and guidance. I am also thankful for the guidance and useful suggestions of my committee members, Associate Professor Dr. Salim bin Said and Dr. Suleyman Aremu Muyibi, during the preparation of this work.

I would also like to thank Dr. Aziz F. Eloubaidy for his direction and encouragement throughout the development of this project. Thanks to all the Hydraulic Laboratory staff, especially Mr. Zainuddin Ismail and Mr. Mohd. Jan Mohd. Daud for their great assistance in the experimental set-up.

I am especially thankful to the government of Malaysia for sponsoring me throughout my studies. Finally, a very special note of gratitude is offered to my family for their patience and encouragement which has helped to make this endeavor successful.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF NOTATIONS

Symbol	Definition
a_L	Longitudinal dispersivity
a_T	Transverse dispersivity
c	Tracer concentration at a point
c_0	Initial tracer concentration
d	Diameter or grain size of soil particle
d_s	Saturation depth of well
d_{10}	Grain size at 10 percent passing
d_{50}	Median grain size, 50 percent passing
D	Aquifer depth
D_{rr}	Dispersion coefficient in radial direction
D_{zz}	Dispersion coefficient in vertical direction
g	Gravititional acceleration
h	Piezometer head
H_r	Total mass of tracer per unit cross sectional per unit time in radial direction
H_z	Total mass of tracer per unit cross sectional per unit time in vertical direction
J	Jacobian matrix
K	Hydraulic conductivity
L	Saltwater depth
P	Pressure

Q	Rate of discharge
r	Radial distance from well
R	Outer radius of the aquifer
R	Ohmmeter reading
r_w	Well radius
S	Storage coefficient
t	Time
T	Transmisivity of aquifer
V	Average velocity of pore fluid
V_r	Radial component of the mass average particle velocity at a point within a pore
V_v	Volume of void
V_z	Vertical component of the mass average particle velocity at a point within a pore
W_d	Weight of dry sample
W_s	Weight of saturated sample
x,y	Spatial coordinate
Z_w	Depth of well
α'	Compressivity of soil
β	Compressivity of water
γ	Density
ρ	Mass density
ρ_0	Initial mass density
θ	Porosity

θ_c	Mass of a tracer per unit time
μ	Absolute viscosity coefficient
ν	Kinematic viscosity coefficient
η, ξ	Local coordinate
ΔM	Mass of water inside the volume of the element
Δt	Time increment

CHAPTER 1

INTRODUCTION

1.1 General

Hydrologists are becoming increasingly interested in optimizing the use of groundwater reservoirs, not only through making the maximum use of the quantity of water available but also by managing the quality of water in the system. Efforts that were done or currently underway include predicting and controlling the movement of a salt water-fresh water interface, mass transport in the flowing groundwater, and predicting quality changes in an aquifer due to changing irrigation patterns and irrigation efficiency.

Fresh groundwater systems have become important sources of potable water throughout the world and many are in contact with saltwater, which, if drawn into the freshwater aquifer system, can diminish the water's potability as well as usefulness for other purposes. The general class of groundwater systems consists of a saturated porous medium where the denser saltwater tends to remain separated from the overlying freshwater. Human activities, such as groundwater abstraction, land reclamation and land drainage have resulted in a drawdown of the groundwater tables and piezometric level, and inflows of saline groundwater. This leads to a rise of the interface between fresh and saline groundwater, with its harmful consequences for wells and the occurrence of saline seepage. As a result of this mechanism, some mixing will occur between the lower salt water and upper fresh water layers due principally to microscopic and macroscopic dispersion. The solute will move in the direction of flow towards the well and the concentration redistribution will occur accordingly. This displacement of the saltwater into freshwater zone directly influences the quality of water pumped from the well. This leads to the necessity of developing techniques for groundwater utilization from such reservoirs to meet the desired water quality constraints.

The prediction of changes in groundwater quality in a complex hydrologic system generally requires simulation of the field problem and making use of deterministic models. One of these techniques is selective withdrawal in which the position and the depth of pumped well (or system of wells) are designed to ensure pumping of certain quality from the aquifers. This investigation concerns the development of a numerical model describing the flow and solute transport of salt pollutant towards a pumped well in a density stratified non-homogeneous unconfined aquifer.

Many basic studies have been conducted to explain the pattern of movement and mixing between freshwater and saltwater, and the factors that influence these processes. These studies have resulted in analytical solutions to simple flow problems with simple boundary conditions. In this study, the numerical solutions for flow and solute transport equations are available in the forms of existing software. In order to verify this numerical model, an experimental laboratory model was designed and constructed to simulate the selective withdrawal problem.

1.2 Objectives

The main objective of this research is to investigate the flow towards a partially penetrating well in a density stratified unconfined aquifer and the convective-dispersive mixing process between the lower saltwater and the upper freshwater layers. Specifically, this may be interpreted as follows:

a) To develop the mathematical formulation for the flow and solute transport, and at the same time to apply constitutive equations that define the behaviour of particular material – fluids and solids.

b) To formulate the boundary and initial conditions for the flow and solute transport equations of groundwater extraction from the partially penetrating well.

c) To apply suitable numerical solutions for the flow and solute transport equations by using existing software that employs finite element method.

d) To design and construct sand box physical model that can simulate the groundwater utilization from density stratified non-homogeneous unconfined aquifer. The experimental model will be used to verify the numerical model.

CHAPTER 2

LITERATURE REVIEW

Many researchers have worked in this field; many of them presented numerical solutions for the flow and convective-dispersion problems, and others developed analytical solutions. In their works, they took into account the flow system of the aquifer and the condition and behaviour of the contaminants.

In terms of mathematical modeling, Huyakorn [1987] developed a three-dimensional finite element model for the simulation of saltwater intrusion in single and multiple coastal aquifer systems with either a confined or phreatic top aquifer. The model formulation was based on two governing equations, one for fluid flow and the other for salt transport. Spatial discretization of three-dimensional regions was performed using a vertical slicing approach designed to accommodate complex geometry with irregular boundaries, layering, and/or lateral discontinuity. On the other hand, Pickens and Lennox [1976] used the finite element method based on Galerkin technique to formulate the problem of simulating the two-dimensional transient movement of conservative or non-conservative wastes in a steady state saturated groundwater flow system. The convection-dispersion equation was solved in the conventional Cartesian coordinate system and in a transformed coordinate system equivalent to the orthogonal curvilinear coordinate system of streamlines and normal to those lines. The model could be applied to environmental problems related to