UNIVERSITI PUTRA MALAYSIA

THREE-DIMENSIONAL FINITE ELEMENT MODELING OF GROUNDWATER FLOW AND SOLUTE TRANSPORT FOR THE LOWER INDUS BASIN, PAKISTAN

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By

ABDUL SAMAD CHANDIO

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Doctor of Philosophy

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DEDICATION

I wish to dedicate this work to my parents and teachers.

Abstract of thesis presented 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 Ir. Lee Teang Shui, PhD

Faculty: Engineering

A relatively thin layer of fresh groundwater exists over a dense saline layer in the study area. A scientific approach is required to harness this fresh water from this layer. Improper well design and indiscriminate pumping might lead to the saline water intrusion from the native dense saline layer. The partially penetrated wells known as skimming wells have been effectively used to restrain the upward movement of the underlying saline water into the overlying fresh zone. The skimming wells not only supplement the scarce irrigation supplies to meet the crop water requirements at critical times but also control the waterlogging. This study was aimed to develop a numerical model that simulates groundwater flow and solute transport. The ultimate goal was to provide feasible solution for skimming the fresh groundwater from the overlying thin layer without saline upconing from the dense layer in the study area.

A three dimensional finite element model (FEMGWST) was developed that simulates the groundwater flow and hydrodynamic dispersion of solute in confined and unconfined aquifers under steady and transient flow conditions. The three dimensional finite element method is relatively complex and requires large memory

and more computational time but it is flexible to simulate the field system precisely and effectively. The model is capable of handling free surface moving boundaries, aquifer geometry, aquifer heterogeneity and anisotropy, well configurations and constant head and concentration boundaries. The saline and fresh waters are miscible fluids with different densities and a layer of marginal groundwater quality is formed between them, hence the assumption of a sharp interface is avoided in the model.

The model is calibrated against field data collected at different agricultural farms located in the Khairpur district in the lower Indus Basin lying between latitudes of 27°20'42" N and 27°19'23" N and longitudes of 68°32'17" E and 68°35'57" E. The main objective of model calibration is to minimize the spatial and temporal difference between observed and model predicted results. The six statistical indices Adjusted R^2, mean absolute error (MAE), root mean squared error (RMSE), Nash-Sutcliffe efficiency or model efficiency (ME), BIAS, and index of agreement (d) were employed to evaluate the goodness of the model simulation for groundwater flow and solute transport. The values of these statistical performance indices showed that the overall model performance for groundwater flow and solute transport mirrors closely that of the corresponding observed data.

The calibrated model was next used to assess the impacts of different well configurations and boundary conditions such as variation in the pumping rate, tube well operation time, number of well strainers, horizontal distance between well strainers, thickness of fresh saline water interface, well strainer length, water levels in the Rohri and KFE canals and their impact on local groundwater levels and salinity of the surrounding area. It was observed that the well pumping rate is the dominant factor in controlling the waterlogging rather than the fluctuation in canals

water level and well screen length. The simulated groundwater salinity was assessed in terms of the temporal variation in the quality of the pumping water and groundwater salinity at the bottom of the well.

It is observed that the saline water intrusion into the fresh groundwater layer is directly related to the well discharge and the intermittent pumping. The depth of useable groundwater below the bottom of the well is a key parameter to suppress the salinity mound developed at the bottom of the well. The model results suggest that the multi strainer wells could effectively suppress the development of salinity mound compare to single strainer wells. However, when the thickness of fresh saline water reduces to 4 m then the quadruple strainer wells can induce the salinity and a salinity mound can develop. From the evaluation of different scenarios it is concluded that strainer spaced at the distance of 12 m offer better performances than those spaced at 8, 4 and 2 m distances to reduce pumping water salinity in all configurations, except for the quadruple strainer well with fresh saline water interface of 4 m. The results of this study provide guidelines to the farmers, managers, scientists, and engineers to adopt appropriate sustainable groundwater development policy and skimming well design to harness the fresh water overlying saline water for irrigation without deteriorating the quality of land.

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

PEMODELAN BERUNSUR TERHINGGA TIGA-DIMENSI AIR BAWAHTANAH DAN PANGANGKUTAN BAHAN-LARUT UNTUK LEMBANGAN HILIR INDUS, PAKISTAN

Oleh

ABDUL SAMAD CHANDIO

Januari 2012

Pengerusi: Profesor Ir. Lee Teang Shui, PhD

Fakulti: Kejuruteraan

Di dalam kawasan kajian terdapat sehelai lapisan nipis air bawahtanah segar terujud di atas satu lapisan masin tumpat. Satu pendekatan saintifik diperlukan demi mengambil air segar daripada lapisan ini. Reka bentuk telanga yang tidak baik serta pegepaman tanpa memilih boleh menyebabkan pencerobohan air masin daripada lapisan masin tumpat yang asli. Perigi tertusuk separa dikenali sebagai perigi menyiring berkesan diguna untuk menghalang pergerakan air masin bawah masuk ke zon segar di atas. Perigi menyiring bukan sahaja menambah kepada sumber air pengairan yang berkurangan demi untuk memenuhi keperluan air tanaman pada masa kritik tetapi juga dapat mengawal bertakungan. Kajian ini bertujuan memajukan sebuah model berangka untuk menyelakukan aliran air bawahtanah dan pengangkutan bahan larut. Tujuan muktamad ialah menghasil jawapan boleh mungkin untuk memungut-siring air bawahtanah segar daripada lapisan nipis di atas tanpa ujud kon masin daripada lapisan tumpat di kawasan kajian.

Sebuah model berunsur terhingga tiga dimensi (FEMGWST) telah dibentukkan untuk menyelakukan aliran bawahtanah dan serakan hidrodinamik bahan larut di dalam akuifer terkurung dan tak terkurung dalam keadaan aliran mantap dan

berubah. Kaedah ansur terhingga tiga dimensi agar complex dan memerlukan ingatan besar serta lebih masa menggira tetapi ianya lebih boleh suai demi menyelakukan keadaan sebenarnya dengan lebih persis dan berkesan. Model itu sesuai untuk menghadapi sempadan permukaan bebas bergerak, geometri akuifer, keheterogenan akuifer dan tak isotropi, konfigurasi perigi dan tulus tetap dan sempadan tumpuan. Air masin dan segar adalah bendalir boleh-larut campur bertumpatan berbeza dan satu lapisan air bawahtanah berkualiti jidar ujud diantara, oleh itu anggapan antara muka tajam diabaikan di dalam model.

Model tersebut ditentukur dengan data yang dikumpulkan di berberapa ladang pertanian di daerah Khairpur di Lembangan Hilir Indus terletak diantara latitud 27^{o} 20' 42"U dan 27^{o} 19' 23"U dan longitud 68^{o} 32' 17"T dan 68^{o} 35' 57"T. Objektif utama penentukuran model ialah untuk mengurangkan perbezaan ruang dan masa keputusan ramalan model dan data. Enam indeks statistik: R^2 terlaras, ralat mutlak purata (MAE), ralat punca min kuasa dua (RMSE), kecekapan Nash-Sutcliffe atau kecekapan model (ME), BIAS dan indeks persetujuan (d) dipakaiguna demi menilaikan kejituan penyelakuan model bagi aliran bawahtanah bertepuan dan pengangkutan bahan larut. Nilai indeks prestasi berstatistik menunjukkan bahawa prestasi model keseluruhan aliran bawahtanah dan pengangkutan bahan larut mencerminkan data cerapan.

Model tertentukur kemudian diguna untuk menaksir impek konfigurasi perigi berlainan dan keadaan sempadan seperti perubahan kadar pengepaman, masa beroperasi perigi tuib, nombor saring perigi, jarak datar antara saring perigi, tebal antara muka air segar masin, panjang saring perigi, paras air di dalam saluran terbuka Rohri dan KFE dan impek terhadap paras tanahair tempatan serta kemasinan

kawasan merangkumi. Diperhatikan bahawa kadar pengepaman perigi adalah faktur berkuasa mengawal bertakungan dibandingkan dengan perubahan paras air dalam saluran dan panjang tabir perigi. Penyelakuan kemasinan air bawahtanah ditaksirkan berasas kepada perubahan semasa kualiti air dipam dan kualiti kemasinan air bawahtanah pada dasar perigi.

Ia diperhatikan bahawa pencerobohan air masin ke dalam lapisan air bawahtanah segar dikait terus kepada kadar aliran perigi dan mengepam terputus-putus.Ukuran dalam air bawahtanah boleh diguna di bawah dasar perigi ialah satu parameter utama demi menindas timbunan kemasinan yang muncul pada dasar perigi. Keputusan perigi menggambarkan bahawa perigi bermulti-saring boleh menindas dengan berkesan pembesaran timbunan kemasinan dibandingkan dengan perigi bersaring tunggal. Akan tetapi, bila tebal lapisan air segar kurang sehingga 4m maka perigi bersaring empat boleh aruh kemasinan dan satu timbunan kemasinan boleh terjadi. Daripada penilaian scenario berbeza ianya didapati bahawa saring berjarak 12m bagi prestasi yang lebih baik jika dibandingkan dengan yang berjarak 8, 4 dan 2m untuk mengurangkan kemasinan air bagi semua konfigurasi kecuali perigi yang bersaring empat dengan keadaan antara muka air segar masin sebanyak 4m. Hasil kajian ini sebagai garispanduan kepada petani, pengurus, saintis dan jurutera supaya mengamalkan polisi membangunkan sumber air bawahtanah yang sesuai dan tertanggung serta mengguna rekabentuk perigi bersiring demi untuk memgumpul air segar di atas air masin untuk pengairan tanpa kemerosotan kualiti tanah.

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A special word of thanks to my parents and friends, especially to my father, for all their support, encouragement and understanding throughout the project.

I certify that an examination committee has met on January 10, 2012 to conduct the final examination of Abdul Samad Chandio on his Doctor of Philosophy thesis entitled "**Three-dimensional finite element modeling of groundwater flow and solute transport for the lower Indus Basin, Pakistan**" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra [P.U.(A) 106] 15 March 1998. The committee recommended that the student be awarded the Degree of the Doctor of Philosophy.

Members of the Thesis Examination committee were as follows:

Professor
Faculty of
Universiti Putra Malaysia
(Chairman)

Professor
Faculty of
Universiti Putra Malaysia
(Internal Examiner)

Professor
Faculty of
Universiti Putra Malaysia
(Internal Examiner)

Professor
Faculty of
University
(External Examiner)

SEOW HENG FONG, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

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:

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

Desa Ahmad, PhD, Ir
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

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not currently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.

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ABDUL SAMAD CHANDIO

Date: 10 January 2012

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