普通高等教育“十二五”规划双语系列教材

NUMERICAL SIMULATION OF GROUNDWATER FLOW—FINITE-DIFFERENCE METHOD

地下水流数值模拟——有限差分法

郑秀清　陈军锋　刘萍　编著

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内 容 提 要

本教材是国内地下水流数值模拟的一本双语教材，内容包括基本理论、Visual MODFLOW 软件使用和实践应用三部分，知识点系统全面。第一部分是地下水流数值模拟的基础理论，讲述了有关基本概念、基本定律、基本微分方程、数学模型的建立和有限差分方法等。第二部分讲述了 Visual MODFLOW 软件的使用步骤，包括水流模型的输入、运行和输出。第三部分为基于 Visual MODFLOW 软件的地下水流数值模拟应用实例，包括地下水库截渗墙建设的数值模拟和水源地保护区划分的数值模拟。

编者根据多年的教学经验和水文与水资源工程专业本科生双语课程"Numerical Simulation of Groundwater Flow"的教学示范总结，并融合了基本的水文地质学基础知识和地下水动力学理论，既注重强化学生的基础理论，又侧重培养学生的动手能力，教材特色鲜明，可作为高等院校水文与水资源工程、地下水科学与工程、市政工程和环境工程等相关专业本科生和研究生的教材。

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ABSTRACT

This bilingual textbook about numerical simulation of groundwater flow, can be divided into three parts including basic theory, Visual MODFLOW software introduction and practical application. The first part describes the basic concepts, fundamental law, basic differential equations, establishment of mathematical model and the finite-difference method. The second part presents the tutorial of Visual MODFLOW software, including the input, run and output of groundwater flow model. Based on Visual MODFLOW software, the numerical simulations of groundwater flow application case are recommended in the third part, including numerical simulation of impervious wall construction and protection zones delineation.

On the basis of many years of teaching experience and summary of bilingual teaching on "NUMERICAL SIMULATION OF GROUNDWATER FLOW" which is setting for Hydrology and Water Resources Engineering specialty, we have integrated basic hydrogeology knowledge and groundwater dynamics theory in the book. This distinctive textbook focuses on not only strengthening basic theory of hydrogeology but also cultivating students' practical ability. So this bilingual textbook can be used by undergraduates and graduates who are major in Hydrology and Water Resources Engineering, Groundwater Science and Engineering, Municipal Engineering and Environmental Engineering.

前　言

地下水是宝贵的自然资源，也是人类赖以生存的物质基础。随着社会经济的快速发展，地下水不合理开发利用和污染问题日益严重，已成为水利、环境、地矿、城建等领域重要的研究对象。地下水流数值模拟是研究地下水流运动规律的强有力工具。

近年来，双语教学作为高校提升教学水平和学生综合素质的教学手段，得到相关教育部门的高度重视，正在逐步走进课堂。此外，国内使用的地下水流的数值模拟软件大多是英文界面和英文说明书，从模拟软件的教学和实践应用角度来看，也迫切需要正式出版一本“地下水流数值模拟”方面的双语教材。编者多年来的双语教学实践表明，课堂教学采用中英文双语教学，不仅能够提高学生的专业知识和地下水流数值模拟的能力，而且可以提高学生的专业英语阅读水平和写作水平。因此，为了适应部分高校教学改革发展，以及改善教材不能与时俱进的局面，适时编写出版了本教材。

全书共分 6 章，第 1 章、第 4 章和第 5 章由太原理工大学陈军锋执笔，第 3 章由太原理工大学郑秀清执笔，第 2 章和第 6 章由太原理工大学刘萍执笔，全书由郑秀清教授统稿，部分图件由臧红飞博士负责完成。在此，我们还要特别感谢研究生任霞、冯晓曦和雷俊琴等对本教材的顺利出版付出的辛勤劳动。

我们对所有为本书修改、出版付出辛勤劳动的同志致以衷心的感谢。本书不当之处在所难免，恳请读者给予指正。

作　者

2014 年 2 月

PREFACE

Groundwater is a precious natural resources and a basic material for human survival. As the social economy advances rapidly, unreasonable exploitation and serious pollution problems of groundwater has attracted more attention from researchers who are engaged in Water Conservation, Environment, Mining, and Civil Construction and other domains. Groundwater flow numerical simulation is viewed as a powerful tool to inquiry the law of groundwater movement.

In recent years, bilingual teaching, which can improve teaching level and students' comprehensive quality, has been paid more attention by Education Departments and is entering into classrooms step by step as a teaching means. In addition, the software of groundwater flow numerical simulation in our country mostly has English interface and instructions. It is urgent to compile and to publish a bilingual textbook about groundwater flow numerical simulation for the sake of teaching and the practical application of simulation software.

Many years experiences of bilingual teaching have tell us that using both English and Chinese in classroom teaching can not only promote the students' professional knowledge and the ability of groundwater flow numerical simulation, but also enhance the students' capacity for English reading and writing. Therefore, in order to adapt to the college teaching reform and development, and improve the situation that the teaching material can't keep pace with the times, we publish this book.

The book is divided into six chapters. The first, fourth and fifth chapters are written by Chen Junfeng of Taiyuan University of Technology; the third chapter is written by Professor Zheng Xiuqing of Taiyuan University of Technology; the second and sixth chapters are written by Liu

Ping of Taiyuan University of Technology, and Professor Zheng Xiuqing does the final compilation and editing. Some of the figures are finished by Dr Zang Hongfei. Many thanks to the graduate students Ren Xia, Feng Xiaoxi and Lei Junqin for doing a lot of hard work for the publication of this book!

We express our heartfelt thanks to all comrades who have been engaged in this book. Improprieties in this book are inevitable, and we will appreciate for your correction.

Authors

February, 2014

Contents

Chapter 1 Introduction

§ 1. 1 Brief of Groundwater

Groundwater is the most precious natural resources for a country. Throughout history, people around the world have used groundwater as a source of drinking water and even today, more than half of the world's population depend on groundwater for survival. Many countries have relied on groundwater for generations, with little thought of using it up or contaminating it. All countries hope to improve their economy by increasing industrial or agricultural production. This goal results in an increase in water use and the potential for contamination. Water managers once believed groundwater was a pure resource, isolated from sources of contamination. However, groundwater contamination has emerged as a major environmental problem in many countries. The public's attention has been drawn to the problem because of the many incidents of groundwater contamination. In the United States, this situation has led to expensive groundwater cleanup, the establishment of groundwater protection laws and environmental protection programs.

1. 1. 1 Importance of Groundwater

Water is vital to man's existence. Early human civilization was centered around springs and streams. The waterhole was the forerunner of a well. Early man copied animals and found that water could be obtained by digging cavities in wadi beds or damp places.

Hidden beneath much of the land surface are groundwater reservoirs-open spaces or voids in rocks which store the largest volume of liquid freshwater on Earth. More than 20 percent of Earth's freshwater resources are here. It is the source of drinking water for most of the world's rural population and is a vital resources, especially in arid areas and on islands, where it may be the only source for potable water. It is essential to maintain soil moisture for crops, lake levels, streamflow, and wetlands. Groundwater from wells and springs is the major source of bottled mineral drinking water.

Groundwater is present in permeable rocks beneath most land areas. Where it occurs, it should be considered a possible alternative supply to surface water. As a water supply, groundwater has the following potential advantages.

(1) Compared with the high costs of constructing surface water reservoirs, the drillings of wells is relatively inexpensive and can be phased in over a period of specified time to meet increasing demand.

(2) The environmental impact of a well is minor.

(3) Many aquifers have large storage capacities so that increasing demand for water during extended droughts can be met more easily.

(4) Groundwater is usually of good chemical and bacterial quality and is unlikely to require treatment other than precautionary chlorination.

Contrary to commonly-held belief, groundwater is a renewable resource. In many parts of the world, groundwater supplies are continually replaced by rainfall and ensuing infiltration although in arid and semiarid regions, the recover rate may be slow or periodic and the recover amount is small. It is important to realize that all artificial withdrawal of groundwater is at the expense of natural discharge. By careful and knowledgeable management, however, the effects of pumping can be controlled to minimize adverse environmental consequences. In the long term, water levels will only decline if groundwater withdrawals exceed the local rates of replenishment. This custom, called groundwater "mining", is more likely to occur in semiarid regions with limited or no replenishment.

1.1.2 Groundwater Resources Management

Groundwater is a renewable resource, Therefore, in order to achieve long-term benefits, not only the sufficient assessment of groundwater potential but also the high efficiency of water use is required. There are many countries in the world where groundwater is one of the major sources of drinking water. With the increasing development of the groundwater resources and the growing impacts of human activities on the aquifers, problems such as declines of groundwater heads and deterioration of groundwater quality have been observed in many places in last decades. Sustainable development strategy and integrated groundwater resources management must be developed and implemented to guarantee the right of use of the limited water resources for our future generations.

To formulate technically reasonable groundwater resources management polices, decision makers always ask questions like:

(1) How long can an aquifer maintain the current rate of groundwater abstraction? What is the safety yield that the aquifer can sustain the continuous abstraction?

(2) What is the capture zone of a water supply well field? What is the most likely pathway of contaminants from domestic wastewater and leaches from solid waste disposal sites? What are the chances that the pollutants from those sources would arrive at water supply wells? And how long it takes? In order to protect the well fields from pollution, a protection zone should be delineated. What is the size of the protection zone?

Providing answers to these questions involves the understanding of the behavior of groundwater flow system and the prediction of the system's response to any stresses. Numerical simulation, a useful tool for groundwater management and protection, is always used in solving these problems. Understanding of groundwater system characteristics is the precondition of building mathematical model. The groundwater flow problems and the groundwater quality problems can be solved efficiently by numerical simulation. In order to quantitatively calculate the available exploitation quantity of groundwater and provide basis for rational development and utilization of water resource, the numerical simulation method is used to establish a three-dimensional numerical simulation model. An optimal scheme is determined to ensure the normal operation of the water source.

§ 1. 2 Process of Groundwater Modeling

The process of groundwater modeling involves a number of different steps and the essential steps are shown as Figure 1. 1.

1. *Defining purpose*

Groundwater models are usually applied for predicting the consequences of the proposed actions such as groundwater development scenarios or waste disposal. Models can be used for analyzing groundwater flow system by assembling and organizing field data and formulating ideas about dynamics of flow systems. Models can be also used for studying processes in generic geologic settings like river-aquifer systems. It is essential to identify clearly the purpose of modeling so that the needs of modeling efforts and accuracy are determined. The purpose of modeling also decides on the dimensionality and time dependency of a model.

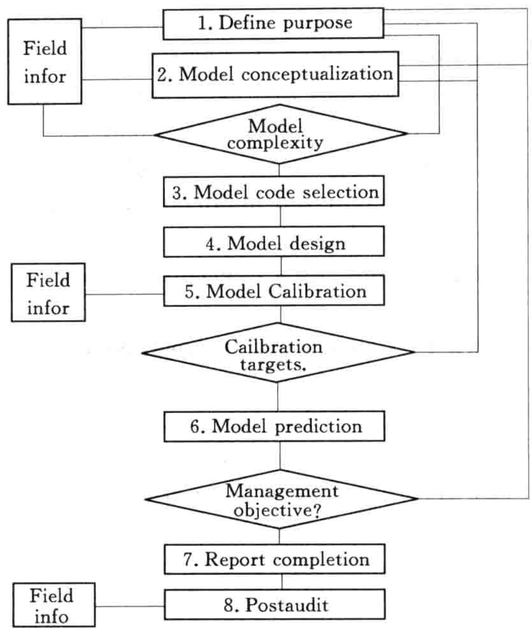

Figure 1. 1 Process of groundwater modeling

Answers to the following questions will help in the determination of the types of model applications and the levels of modeling efforts:

(1) Will the model be used for the prediction of system's response, analysis of flow systems, or study of the processes in a certain generic geologic settings? (Really necessary to build a model?)

(2) What questions do you want the model to answer? (Questions to be answered by the model.)

(3) Can an analytical model provides the answer or must be a numerical model is constructed? (Analytical or numerical model?)

Examples of prediction the consequences of a proposed action:

(1) Groundwater development scenarios: Extension and magnitude of the cone of depression around a pumping station.

(2) Groundwater pollution: Plume of groundwater contaminants from a waste disposal site.

(3) Interaction between groundwater and environment impacts of a reservoir on groundwater level.

Example of interpretation:

(1) Framework for assemble field data synthesizing field data; testing assumptions about the system; indicating the further field work.

(2) Flow system analysis: pathlines, flow rate, pattern of recharge and discharge boundary conditions.

(3) Sensitivity analysis: Identification of important system parameters.

2. *Building conceptual model*

The purpose is to simplify the field problem and organize the associated field data so that the system can be analysis and modeled more readily. Conceptual model is a quantitative representation of groundwater systems in terms of aquifer-aquitard layers, boundary conditions hydrogeological parameters, hydrological stresses, flow patterns, and water balance components. Field visits are necessary to gain the modeler first impression about the area to be modeled. The conceptual model is simplified as much as possible yet retain the important hydrogeologic condition so that it adequately reproduces system behavior.

Steps in Building a Conceptual Model

Step 1 Construction hydrogeologic framework.

(1) Schematization of aquifer systems (geological cross sections).

1) Defining hydrogeological units.

2) Classification of hydrogeological units.

3) Hydrogeological cross sections.

4) Types of aquifers (hydrogeological cross sections).

5) Thickness and lateral extent of aquifers and confining beds (hydrogeological cross sections).

Lateral extent of aquifers can be determined from cross sections and then projected on the map; Natural hydrogeological boundaries are boundaries of the extent of aquifers; Construction of contour maps of groundwater level, elevation of bottoms of aquifers and confining beds; Aquifer thickness can be calculated from contour maps, or directly calculated from cross sections; Construction of isopach map of aquifers and confining beds.

(2) Boundaries of aquifer systems (hydrogeological cross sections).

1) Types of boundaries.

Physical boundaries (fixed)—Impermeable rocks; Impermeable faults; Large bodies of surface water.

Hydraulic boundaries (movable)—Groundwater divides; Streamlines.

2) Mathematical representation.

3) Setting boundaries.

Hydrogeological boundaries—Impermeable rocks; Impermeable faults; Large rivers, lakes, and oceans; Regional groundwater divides.

Distant boundaries—Artificial boundaries for transient simulation where head and flow are not influenced by the stresses.

Hydraulic boundaries—Groundwater divides; Streamlines; Groundwater head contour line.

4) Simulating boundaries.

Specified head boundaries—River; Lake; Ocean; Water level.

Specified flow boundaries—Seepage to stream, spring flow, underflow, seepage to/from bedrocks, local hydraulic boundaries.

No-flow boundaries—Impermeable bedrock, impermeable fault zone, seepage a groundwater divide, a streamline, a freshwater/saltwater interface.

Head-dependent flow boundaries—Leakage to/from river, lake, reservoir.

(3) Hydrogeologic parameters.

1) Parameters—Hydraulic conductivity, K; Transmissivity, $T=Km$; Storage coefficient, S_s; Specific yield, S_y; Porosity, n; and so on.

2) Pumping tests.

3) Laboratory tests.

4) Empirical data.

(4) Extent and rate of areal recharge (precipitation, irrigation).

(5) Extent and rate of areal discharge (evapotranspiration).

(6) Locations and rate of wells (discharge/recharge).

(7) Spatial and temporal distribution of interaction between groundwater and surface water (river, canal, lakes, spring flow).

(8) Locations of observation wells and Hydrograph of groundwater of groundwater head.

Step 2 Defining the flow system.

Conceptualize the movements of groundwater through the system.

(1) General direction of groundwater flow.

(2) Pattern of recharge and discharge.

(3) Connection between ground-surface water.

(4) Information for analysis—Groundwater head contour maps; Hydrochemical information; Isotopes; Groundwater temperature information; Hydrographs of groundwater head; Hydrographs of surface water level.

Step 3 Preparing the water budget.

Groundwater balance: Inflow+Outflow=Changes in storage.

Inflow—Precipitation; surface water; Underflow; Irrigation.

Outflow—Evapotranspiration; Spring flow; Baseflow to stream; Pumping; Underflow.

3. *Selecting computer code*

A computer code is a computer programme which solves the mathematical model of groundwater flow or contaminant transport numerically. There are many computer codes available. The selection of a suitable code depends on the complexity of the conceptual model and the purpose of study. The main considerations are:

(1) Types of model: flow model, particle tracking or solute transport model.

(2) Time dependency: steady or transient model.

(3) Dimensionality: one, two, quasi-three, or fully three dimensional model.

(4) Ability to describe the aquifer properties: homogeneous or heterogeneous; isotropic or anisotropic media.

(5) Ability to include various hydrological stresses.

(6) User friendliness.

(7) Requirements on the computer facility.

Widely-applied model—MODFLOW; MOC3D; MT3D; MODPATH; Processing Modflow (PM); Visual Modflfow (VM); Groundwater Modeling System (GMS); Finite Element Modflfow (FEM).

4. *Designing numerical model*

The design of numerical model includes the selection of modeling area, design of model grids, selection of stress periods and time steps, setting model boundaries and initial conditions. The conceptual model will be the bases for the design of the numerical model. The purpose of the modeling will dictate the sizes of grids and time steps. The memory and computing time of computers and the computer code may have limitations on total number of grids and time steps.

5. *Determination of model inputs*

The inputs to the model include initial and boundary conditions, hydrogeological parameters, and hydrological stresses. The data for all these inputs have to be entered to all grid points for all stress periods.

(1) Data for defining physical framework.

Geologic map and cross sections showing the areal and vertical extent and boundaries of the system.

1) Topographic map showing surface water bodies and divides.

2) Contour map of land surface elevation.

3) Contour maps showing the elevation of the base the stratigraphic units.

4) Maps showing the extent and thickness of stream and lake sediments.

(2) Hydrogeologic framework.

1) Schematization of aquifer systems.

2) Thickness and lateral extent of aquifers and confining beds.

3) Boundaries of aquifer systems.

4) Maps and cross sections showing the storage properties of the aquifers and confining beds.

5) Maps and cross sections showing the distribution of hydraulic conductivity/transmissivity.

6) Maps showing the extent and thickness of stream and lake sediments.

7) Groundwater head contour maps.

8) Locations of observation wells and measurements.

(3) Hydrological stresses.

1) Extent and rate of areal recharge (precipitation irrigation).

2) Extent and rate of areal discharge (evapotranspiration).

3) Locations and rate of wells (discharge/recharge).

4) Spatial and temporal distribution of interaction between groundwater and surface water (river, canal, lakes).

5) Spatial and temporal distribution of springs.

6) Locations of observation wells and hydrographs of groundwater head.

6. *Calibration of the model*

(1) Why to calibrate the model? The purpose of calibration is to establish the model that can reproduce the field measured groundwater heads or concentrations.

(2) How to calibrate the model? The calibration forces the model calculations approximate the field measured values through the adjustment of aquifer parameters or stresses by trial-and-error method or automated parameter estimation method requiring the measurements of groundwater heads or concentrations.

(3) Assessment of calibration. Mean error; maximum error; root mean square error (RMS).

(4) Sensitivity analysis. Objectives—Uncertainty of model parameters on model results; Identification of most important parameters.

Sensitivity coefficients—Head or concentration; RMS (root mean square).

Procedures for sensitivity analysis—Before and after model calibration; Systematic vary parameter values.

7. *Verification of the model*

To check whether the calibrated model has the predictive power, the calibrated model is applied to another period of time where a second field data are available. The model should also be able to reproduce the field measured values of groundwater heads or concentrations with hydrological stresses in this period.

8. *Application of the model*

The calibrated model is used to predict the response of the aquifer system to future events. In the prediction the model is run with calibrated aquifer parameters and future hydrological stresses. Some hydrological stresses are the proposed actions (such as abstraction). Others are natural uncontrolled stresses (such as recharge from precipitation).

9. *Presentation of results*

Clear presentation of modeling processing and results is essential for the effective communication of the modeling effort. The report on the modeling study should include chapters like:

(1) Introduction.

(2) Hydrogeological conceptual model.

(3) Numerical model setup.

(4) Model calibration.

(5) Model application.

(6) Summary and conclusions.

10. *Postaudit*

(1) Validation of the model prediction.

(2) Not yet a normal part of modeling.

(3) Groundwater models did not accurately predict the future due to ① error in conceptual model or/and ② errors in estimation of assumed future stresses.