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Ground Water Flow Modelling Using MODFLOW –A Review

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A B S T R A C T

Significant advances of groundwater flow modeling have been driven by the demand to predict regional impacts of human inferences on groundwater systems and associated environment. Large scale transient groundwater models have been built to analyze regional flow systems, to simulate water budget components changes, and to optimize groundwater development scenarios. The main intent of the paper is to present a comprehensive review on application MODFLOW package for ground water management and development. Specific methodologies for regional groundwater flow modeling are descried.

Introduction

Groundwater is a precious and most widely distributed resource of the earth, which is required for agriculture, industry and domestic purposes. It gets annual replenishment from the meteoric precipitation.70 percent of the earth's surface is covered with water. The reality, however, is that 97.3 % of the total water on earth is saline and only 2.7 % is available as fresh water. About 77 % percent of this fresh water is locked up in glaciers and permanent snow. About 11 percent of the resources are available as extractable ground water within 800 m depth and about 1 percent is available as surface water in lakes and rivers (CGWB, 2007; MoWR, 2009). Due to rapid urbanization and industrialization, the need for water is ever increasing. The requirement of water in a developing country like India, where more than 90% of rural and nearly 30% of urban population depend on groundwater for meeting their drinking and domestic requirements (CGWB, 2007). As present, nearly one fifth of all the water used in the world is from groundwater resources. Currently, water resources management has to consider a river basin as an integrated system where interactions among surface water, groundwater, and water resources use and effects on ecosystems take place. Decision-makers require adequate information on these interactions in order to formulate sustainable water resources development strategies. Groundwater models play an important role in the development and management of groundwater resources, and in predicting effects of management measures. With rapid increases in computation power and the wide availability of computers and model software, groundwater modeling has become a standard tool for professional hydro geologists to effectively perform most tasks.

GIS has emerged as an effective tool for handling spatial data and decision making in several areas including engineering and environmental fields (Stafford, 1991; Goodchild, 1993). GIS provides a means of representing the real world through integrated layers of constituent spatial information (Corwin, 1996). Most GIS, can easily access overlay and index operations but cannot model groundwater flow and transport processes. However, coupling a GIS to process-based groundwater models can provide an effective tool for data processing, storing, manipulating, visualizing and displaying hydro geological information. Data used in groundwater modelling consists of four categories: (1) the aquifer system stress factor, (2) the aquifer system geometry, (3) the hydro geological parameters, and (4) the main measured variables (Gogu *et al.*, 2001)

A well designed GIS database can significantly reduce the time required for data preparation, processing and presentation during the modelling process. Use of groundwater models in hydrogeology mainly includes the simulation of steady or transient sate groundwater flow, advection, hydrodynamic dispersion, and multi-component chemical reaction. In recent years, the use of GIS has grown rapidly in groundwater assessment and management research works. Lasserre *et al.*, (1999) developed a simple GIS linked model for ground water nitrate transport in the IDRISI GIS environment. Visual MODFLOW is also an user friendly software that has ability to generate 3D visualization graphics and import GIS data. Xu *et al.*, (2009) used MODFLOW 2000 (Harbaugh *et al.*, 2000) coupled with GIS to simulate the groundwater dynamics. All of them vary both in space and time, thus adopting a Geographic Information System (GIS) in association with a model is helpful. Coupling GIS technology with a process-based groundwater model may facilitate hydro geological and hydrologic system conceptualization and characterization (Hinaman, 1993; Kolm, 1996; Gogu *et al.*, 2001), thus also a proper adaptation of the groundwater flow model to the area under study (Brodie, 1998). In most of groundwater modelling softwares such as FEFLOW, MODFLOW, GMS (Groundwater Modelling System) there is an interface that links vector data through compatible GIS formats *i.e.* .shp, .lin, .dxf etc. and raster data formats i.e. .tif, .bmp, .img etc

Groundwater flow models have been used: (1) as interpretative tools for investigating groundwater system dynamics and understanding the flow patterns; (2) assimilation tools for analyzing responses of the groundwater system to stresses; (3) as assessment tools for evaluating recharge, discharge and aquifer storage processes, and for quantifying sustainable yield; (4) as predictive tools for predicting future conditions or impacts of human activities; (5) as supporting tools for planning field data collection and designing practical solutions; (6) as screening tools for evaluating groundwater development scenarios; (7) as management tools for assessing alternative Polices; and (8) as visualization tools for communicating key messages to public and decision-makers.

This paper presents an overview of groundwater flow modeling. A brief history of regional groundwater flow modeling is reviewed. Special issues in regional groundwater modeling are discussed, and specific methodologies for constructing regional groundwater flow models are then summarized.

Basic principal of ground water modeling

MODFLOW is programmed under the FORTRAN 77 (American National Standards Institute 1978) language environment with the finite–difference method to describe the movement of groundwater flow. It was developed by McDonald and Harbaugh (1984) of US Geology Survey in 1984 and had been updated for three times including MODFLOW-88(McDonald and Harbaugh 1988), MODFLOW-96 (Harbaugh and McDonald, 1996) and MODFLOW-2000 (Harbaugh *et al.*, 2000). The newest version of MODFLOW-2000 could be compiled by FORTRAN language of Visual Studio program and general language of C could be used here.

Ground Water flow model under steady and transient state by using finite difference method with the help of Visual MODFLOW (Guieger and Franz, 1996). The theoretical background for the ground Water modeling is presented in this section. The three-dimensional movement of ground water of constant density through porous earth material may be described by the following partial differential equation.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=-S_s\frac{\partial h}{\partial t}$$

Where

Kxx, Kyy and Kzz are values of hydraulic conductivity along the X, y and z co- ordinate axes which are assumed to be parallel to the major axes of hydraulic conductivity

h is piezometric head.

W is a volumetric flux per unit volume and represents sources and/ or sinks of Water.

Ss is the specific storage of the porous material.

t is time.

Equation describes ground water flow under non equilibrium condition in a heterogeneous and anisotropic medium, provide the principal axes of hydraulic conductivity are aligned with the co-ordinate directions.

Application of GIS and MODFLOW

Modeling of groundwater basins requires large sets of data on the hydrogeological framework, hydraulic parameters, hydrological stresses and measured groundwater heads. All these data are stored and presented in many different forms and scales such as maps, graphs, tables, computer databases, or spreadsheets. A Geographical Information System (GIS) represents a powerful set of tools that can significantly improve the processing of spatial data. Coupling GIS and groundwater models can be achieved using three techniques: loose coupling, tight coupling, and embedded coupling (Gogu *et al.,* 2001). Loose coupling is when GIS and the model represent distinct software packages and the data transfer is made through input/output model predefined files. The GIS software is used to pre-process and post-process the spatial data. An advantage of this solution is that the coupled software packages are independent systems, facilitating potential future changes in an independent manner. Most applications of GIS in groundwater modeling use the loose coupling technique. In tight coupling, an export of data to the model from GIS is performed, but the GIS tools can interactively access input model subroutines. In this case, the data exchange is fully automatic. An example of this coupling is the groundwater model link (Steyaert and Goodchild, 1994) between the ERMA spatial database scheme and MODFLOW, MODPATH, and MT3D finite difference software packages.

Application of groundwater modelling using MODFLOW

Abdulla and Tamer (2006) carried out processing modflow version (PM5) is used in the study to simulate the groundwater flow for both steady and transient condition to forecast the future changes that occurred under different stages and to investigate different scenarios of artificial groundwater recharge to evaluate their effect on the water table.

A steady state groundwater model has been developed by using visual mudflow. The model water balance was calculated. The loosing and gaining reaches of the river were identified and the groundwater and surface water exchange was quantified (Shibru Wake, 2008).

Chen and Chen (2003) conducted a numerical modeling study using MODFLOW and MODPATH to investigate the effects of stream aquifer fluctuations, aquifer properties, the hydraulic conductivity of streambed sediments, regional hydraulic gradient and recharge and evapotranspiration rates on stream aquifer interaction. They concluded that bank storage solely caused by stage fluctuations differs slightly between losing and gaining streams

Mahesh Kumar (2004) developed a steady state ground water flow 'North East Musi Basin using Finite Difference Method under MODFLOW package by assuming 8 to 10% of annual recharge. From the water balance computation in steady state, the recharge is estimated as 2.4 MCM out of which 1.1 MCM is Contributed by lakes. Outflow and draft were estimated as 0.4 MCM and 2.1 MCM respectively

Sarada (2006) developed a steady state ground water flow model of upper Musi basin using MODFLOW package. The ground Water draft (output) has been estimated about 177.5 MCM and river leakage is estimated as 120 MCM and outflow being 0.4 MCM. They assumed the recharge of 8- l0% from the total annual rainfall according to model for the entire Musi Basin simulated by Massuel *et al.*, (2007), Mean annual simulated recharge is 1176 MCM (17% of total rainfall) While annual Pumping is estimated at 1235 MCM. Simulated base flow is 23 MCM while river leakage is less than 1 MCM. Among the total simulated annual recharge, ground Water irrigation return flow to the aquifer can be estimated at 370 MCM and artificial recharge at 124 MCM. Natural recharge from rainfall accounts for 652 MCM. The sustainable ground water withdrawal yield over the period is around 1,220 MCM for the total basin

Rajamanickam and Nagan (2010) conducted a study to model a river basin at the downstream of Karur Town using Visual MODFLOW 2.8.1 version. The study area was limited to 320 km² which was divided into 4572 cells with grid size of 350m x 200 m with two layers. The groundwater monitoring data, lithology, hydro geological parameters, topography, rain fall data obtained from PWD, CGWB, Survey of India, and India Metrological Department are used in the model. The MODFLOW and MT3D models are calibrated and validated for simulation of the groundwater quality for next 15 years under five difference scenarios. The simulation results show there is no improvement in groundwater quality even the effluent meet the discharge standards for the next ten years. When the units go for zero discharge then there will be an improvement in the quality of groundwater over a period of few years.

Ground water modeling is increasingly recognized as powerful Quantitative tool available to hydrogeologists for evaluating ground water systems. A ground water model is a simplified version of the real system that approximately simulates the ground water flow and response relations of the system.it plays an important role in understanding the water systems behavior when subjected to stress and changing conditions. The Visual MODFLOW model allows considerable flexibility in modeling environment for practical applications in 2 and 3-dimensional groundwater flow for a multilayer aquifer of different types of groundwater basins. Though many other models are in use in India and abroad for groundwater modeling of different groundwater basins having various management regimes. The Visual MODFLOW is a new model, which is more Users friendly and works for small to large groundwater basins having multilayer aquifer systems.

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