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A Comparative View of Groundwater Flow Simulation Using Two Modelling Software - MODFLOW and MIKE SHE

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Abstract

The sustainable use and management of groundwater resources is now a great challenge for many countries of the world. Recently groundwater modelling has been an effective way to address this challenge. There are a number of modelling software exist to simulate groundwater flow. Among them two modelling software - MIKE SHE and MODFLOW were used to develop two individual groundwater models and a comparison of these model's output is presented in this paper. The main difference between these two modelling software is that MIKE SHE includes unsaturated zone whereas MODFLOW deals with saturated zone only. Using existing hydro-geological and meteorological data, two models were developed and calibrated for the high Barind area of Bangladesh in layers of five distinct vertical deposits, namely Clay Top, Upper Aquifer, Clay Middle, Lower Aquifer and Clay Bottom). The difference of groundwater flow hydrographs from two models and the probable reasons behind the difference are discussed. The important calibration parameters are being depicted in this paper.

Keywords: Groundwater Modelling, MIKE SHE, MODFLOW, Unsaturated zone, Hydro-geologic data, Meteorological data.

Introduction

Groundwater is a vital source of water throughout the world because of its availability and general good quality [1]. Few years ago ground water was taken as granted for safe use, but recent circumstances indicate that ground water is seriously vulnerable to depletion in some countries. Because of this threat, it is important to understand the processes that make ground water available for use. With the development of groundwater investigations, it is important to understand the development of comprehensive conceptual models and to analytical solutions or numerical methods of groundwater modelling. Modelling and simulation are popular instruments to manage groundwater resources now. Groundwater models simulate the behaviour of a groundwater system using mathematical equations. Generally groundwater models evaluate changes in the water balance of an aquifer caused by pumping, land-use changes, climate, etc. and how these changes affect groundwater storage, stream flow, lake levels, and other environmental variables.

In recent times there are many groundwater modelling software available to perform this job. Among them MIKE SHE, an Integrated hydrological catchment model has been widely used in many parts of the world to study a variety of water resource and environmental problems under diverse climatologically and hydrological regimes [2, 3]. For example MIKE SHE has been applied to examine the dynamics of the hydrological system, to assess water management options to restore depleted groundwater resources, to measure the relative contribution of different components of the hydrological system in a complex environment etc. [4, 5]. At the same time MODFLOW is another widely used groundwater modelling software which has been used for many groundwater studies [6, 7]. In Bangladesh these two are mostly used groundwater modelling software. Therefore many institutions in Bangladesh are interested in using both software and try to compare the results for management decisions. This study explores the use of these two models for assessing groundwater resource of the study area. A modified version of MIKE SHE (after [8]) has been used in this study; which can describe the main physical processes of the hydrological cycle and Visual MODFLOW has also been used here. Each model has its own advantages over the other. As such this study is intended to compare these two models and identify the suitability of the model for simulating the groundwater resource of the study area.

Study Area

The study area lies within the Barind area which is situated in the North western part of Bangladesh and known as the High Barind. The area is bounded by Indian Territory on the North and part of West, Ganges River on the South, Mohananda river in the west. The geographic boundary of the study area is Latitude 24.3703 and Longitude 88.2866 for the South Western corner and Latitude 25.2141 and Longitude 88.6968 for the North Western corner and covers approximately 22 km^2 [9]. It is the driest part of Bangladesh; normally there is no rain from November to April. The mean monthly average rainfall from November to April varies only from 12 mm to 20 mm, although the annual rainfall varies from a minimum of 1000 mm to a maximum of 2000 mm [10]. Dry season irrigation in the project area is mainly done from the groundwater. The operation of few thousands of deep tubewells (DTWs) for irrigation during dry periods creates problems for operation of shallow tubewells, hand tubewells and dug wells. The High Barind area is very different from other areas of Bangladesh as the groundwater flow and available water resources to a large extent are controlled by the ridge and deep incised channels at the periphery. It also contains relatively thick impermeable clay layer and limited aquifer extent in the area [10].

MIKE SHE

MIKE SHE is a comprehensive, deterministic, fully distributed, physically based, user-friendly hydrologic modeling tool that can simulate water movement over and under the Earth's surface i.e. the entire land phase of the hydrologic cycle. Danish Hydraulic Institute (DHI) has developed the software MIKE SHE which is originally derived from the Système Hydrologique Européen, SHE [11 - 12]. MIKE SHE includes both simple and advanced process descriptions to maximize computational efficiency. It can easily link the regional and local scale models. The seamless link to GIS (Geographic Information System) shape files for all distributed parameters saves time and effort. MIKE SHE was developed to model water movement, including overland flow, rivers and lakes, saturated and unsaturated flow, and evapotranspiration [3, 13]. Previously it was especially used for irrigation studies [14]. Here catchment characteristics and input data are represented in square grids only and the governing equations are solved using finite difference methods [14]. The reader is referred to [3, 8, and 15] for a complete description of the model structure and setup.

MODFLOW

US Geological Survey originated software Visual MODFLOW, is a three-dimensional groundwater flow modeling environment for practical applications and contaminant transport simulations. It solves a system of equations describing the major flow and related processes in the hydrological system using finite difference methods. It is being extensively used worldwide to carry out research in the field of groundwater resource management. A full description of the capabilities of MODFLOW can be found in [16, 17].

The Basic Governing Equations

The governing equation for three-dimensional flow in saturated porous media for both MIKE SHE and MODFLOW is the three-dimensional Bousinesq equation (Equation 1), which is the combination of the mass conservation and Darcy's law

$$\frac{\partial}{\partial x}(K_{XX})\frac{\partial h}{\partial x}+\frac{\partial}{\partial y}(K_{YY})+\frac{\partial}{\partial z}(K_{ZZ})\frac{\partial h}{\partial z}+W=S_S\frac{\partial h}{\partial t} \quad (1)$$

where, K_{xx}, K_{yy}, and K_{zz} = values of saturated hydraulic conductivity along the x, y, and z coordinate axes (L/T), which are assumed to be parallel to the principal axes of hydraulic conductivity tensor; h= potentiometric /hydraulic head (L); W= volumetric flux per unit volume representing sources and/or sinks of water, with W<0.0 for flow out of the groundwater system, and W>0.0 for flow into the groundwater system (T^{-1}); S_S= specific storage coefficient of the porous material (L^{-1}).

In MIKE SHE overland flow is calculated by solving diffusive wave approximation in two horizontal directions of the Saint Venant equations (Equation 2, 3 & 4) which are based on conservation of mass and momentum equation. After simplification the equations come as

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}(uh)+\frac{\partial}{\partial y}(vh)=i \quad (2)$$

$$uh=K_x(-\frac{\partial z}{\partial x})^{\frac{1}{2}}h^{\frac{5}{3}} \quad (3)$$

$$vh=K_y(-\frac{\partial z}{\partial y})^{\frac{1}{2}}h^{\frac{5}{3}} \quad (4)$$

Where, (x,y) is the Cartesian coordinates in the horizontal plane, z= z_g + h, z_g(x, y) = ground surface level; h(x, y) = flow depth above the ground surface; u(x, y) & v(x, y) = flow velocities in the x- and y-directions respectively; i(x, y) = net input into overland flow (net rainfall less infiltration); uh & vh = discharge per unit length along the cell boundary, in the x- and y-directions, respectively, K_x & K_y = Strickler coefficients ($K_{x/y}=\frac{u}{h^{2/3}S_{f(\frac{x}{y})}{}^{1/2}}$)

In MIKE SHE flow in the unsaturated zone is calculated by a Richards equation (Equation 5), which is the combination of mass conservation principle and Darcy's law.

$$\frac{\delta}{\delta x}\left(K\frac{\delta\Psi}{\delta x}\right)+\frac{\delta}{\delta y}\left(K\frac{\delta\Psi}{\delta y}\right)+\frac{\delta}{\delta z}\left(K\frac{\delta\Psi}{\delta z}\right)+\frac{\delta K}{\delta z}=\frac{\delta\theta}{\delta t} \quad (5)$$

Where, hydraulic head gradient, h = Z (gravitational head) + (Pressure head); K= unsaturated hydraulic conductivity; θ = the volumetric water content [L^3 L^{-3}], t = time.

In MIKE SHE evapotranspiration is calculated by the methods proposed by Kristensen and Jensen [18] that includes canopy interception, evaporation from the canopy, plant transpiration, and soil evaporation.

Differences between MIKE SHE and MODFLOW

While MODFLOW and MIKE SHE both solves the same physical problem using the finite-difference method, there are some significant differences between the two models that are presented in Table 1.

Criteria	MODFLOW (by USGS)	MIKE SHE (by DHI)
Basic modules	Only 2 modules: Channel/River Flow and Saturated/Groundwater Flow	5 modules: Overland Flow, Channel Flow, Evapotranspiration, Unsaturated Flow & Saturated Flow
Recharge	Included as an upper boundary condition, a calibration parameter	Calculate recharge by water balance simulation
Internal inactive zones	Simply treated as cells with a very low hydraulic conductivity	Ignores in the solution
Grid	Variable finite difference	Square
Model layer	Confined aquifer is specified by transmissivity value and aquitard is specified by leakage value. No need of elevation data	The layer is characterized by horizontal and vertical hydraulic conductivity and a top and bottom elevation
Horizontal hydraulic conductivity	Anisotropic	Isotropic
Vertical hydraulic conductivity	Uses the leakage (1/T) between layers	Vertical hydraulic conductivity (L/T) for each layer
Drain levels	Time varying	Not time varying
Riverbed hydraulic conductivity	Time varying	Cannot vary with time
Interception:	Should be used DUFLOW or other rainfall runoff model	No need of another model
Overland and Channel Flow	Manning's roughness coefficient is used	Strickler roughness coefficient is used
Unsaturated Zone Modelling	Not Included	Included
Saturated Zone (SZ) Modeling	Includes storage coefficient, saturated hydraulic conductivity, effective porosity, location of abstraction and recharge well, pumping & recharge rates	Includes storage coefficient, saturated hydraulic conductivity, drainage depth, time constant for drainage routing, specified flow, gradient & head at boundaries, location of abstraction & recharge well, pumping & recharge rates, vertical node discretization
Reservoirs, & Horizontal Flow Barrier	Included	Not included
Water Density	Can vary from cell to cell. Density depended head is calculated.	Not included
Snow Melt	Not included	Included
Finer Model Grid	Can be made for a specific area of interest, within main model	A separate sub - model needed with the generated data from

		main model
Calibration	Against observed hydraulic heads	Against observed hydraulic heads, river water level and flow
Auto Calibration	Possible for some parameters	Not included
Water Quality Model	3-D	2-D, No chemical reaction is considered
User Interface	Much easier, can be learned quickly from the users' manual.	complicated and a training program is suggested to learn
Operation Speed	Much faster	Take more time

Table 1. Comparison between MODFLOW and MIKESHE.

Groundwater Modelling using MIKE SHE and MODFLOW

In this study two groundwater models were developed using MIKE SHE and MODFLOW to simulate the groundwater level (GWL) and comparison were made between these two GWLs. At first the MIKE SHE model was developed for the period 1997 to 2003 and calibrated by adjusting parameters and finally model was validated for a certain data series. Then groundwater recharge was estimated using a water balance model of the calibrated MIKE SHE model. With that groundwater recharge taken from MIKE SHE model a MODFLOW model was developed and simulated GWL was found. No calibration was done for the MODFLOW model in this study. The input data required for the two models are:

- Rainfall and evaporation data for the entire study area
- Groundwater level to define the initial and boundary conditions and for calibration and validation
- Lithological data along with top and bottom elevations of different geological layers
- Aquifer properties for horizontal and vertical hydraulic conductivities, specific yield and specific storage distributions for different layers
- Land use, soil type, and topographic data for the entire study area
- Groundwater abstraction data

During model development, the study area was discretized into grids of 500m square cells. The model had 186 rows and 85 columns and total of 8945 active cells in 5 distinct hydro-stratigraphic layers. Considering lithological variations and groundwater flow capacity, 5 layers have been demarcated within the studied depth in the study area as Clay Top, Upper Aquifer, Clay Middle, Lower Aquifer and Clay Bottom. In the study area Upper Aquifer and Lower Aquifer are interconnected. Clay Middle is not a continuous layer. As a result both the aquifers act as a composite aquifer in the study area. One geological cross-section of the formations at Northing 756000 is shown in Figure 1.

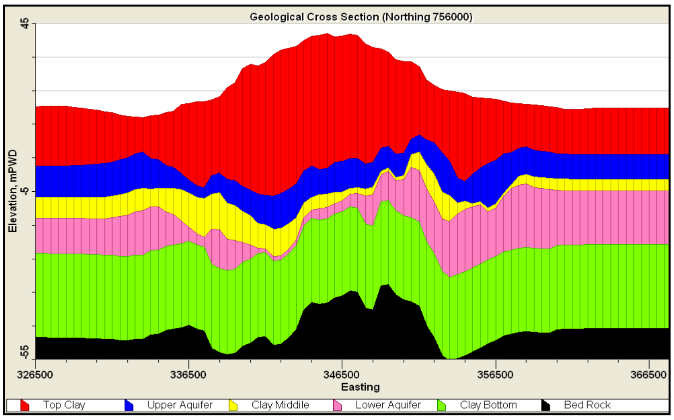

Figure 1: Cross Section of Formations at Northing 756000

Important Calibration Parameters

The MIKE SHE model was calibrated for the period 1997 to 2003 and validated for January 2004 to December 2005 against the observed GWLs at different locations where measured GWLs were available. During calibration of the MIKE SHE model, overland leakage coefficient, soil properties like unsaturated hydraulic conductivity & soil moisture tension relationship, vertical hydraulic conductivity, storage coefficient and maximum bypass ratio of net rainfall were found to be important calibration parameters. Among them overland leakage coefficient was found to be the most sensitive calibration parameter as unsaturated zone of the study area is thick enough. After calibration of the MIKE SHE model the recharge values were extracted from the calibrated MIKE SHE model. That recharge value was directly used in the MODFLOW model development.

In general MODFLOW includes recharge as an upper boundary condition to the groundwater model, where recharge is defined as the amount of water reaching the groundwater table after accounting for evapotranspiration, surface runoff and changing storage in the unsaturated zone. In MODFLOW it is usually done by applying a constant or varying fraction (rule-of-thumb) to the measured precipitation data. In most cases, the model results are very sensitive to this fraction and since there is little data, it assumes a starting value and uses this as a calibration parameter. Thus the amount of recharge is adjusted during the calibration process until the measured groundwater levels match the calculated values.

Normally recharge is the main calibration parameter of MODFLOW model. The other input data and parameters are kept same during the development of the MODFLOW model. The main intention of doing so is to examine and compare the results of both the model.

However, the overall calibration of the MIKE SHE model was acceptable and the GWL hydrographs from MODFLOW had good similarities with MIKE SHE GWL hydrographs.

But there is scope for further improvement. Some of the reasons of deviation between observed and simulated GWLs identified as:

- Exact field abstraction data were not available, there was uncertainty in calculating crop water requirement and irrigation demand, as such, the estimation for irrigation water abstraction might not be accurate enough;
- Distribution of irrigation water extraction gave overestimation of drawdown in areas with low density of irrigation tube well, and underestimation of drawdown in areas with a high density of irrigation tube well;
- The geological structure of the High Barind area is more complex than assumed and it is challenging to obtain a good match between observed and simulated values with large grid size, as many local features may be missed.

Groundwater Flow Hydrographs

In the study area there were 11 locations where observation wells were available to get the observed GWLs. Simulated GWLs from both the MIKE SHE and MODFLOW models were compared with observed GWLs at those 11 locations. Among them one representative comparison plot of hydrograph is presented in Figure 2.

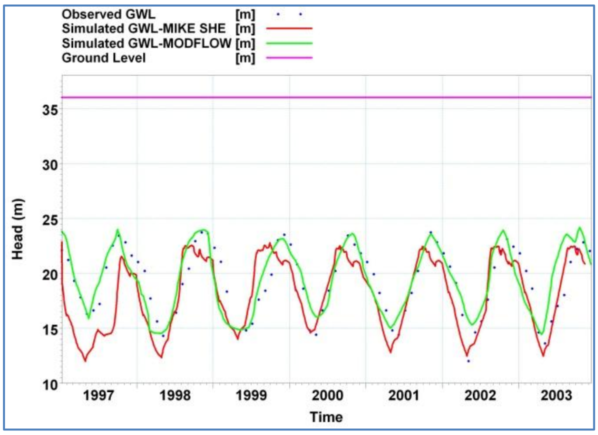

Figure 2: Comparison of simulated GWL Hydrographs from two models with observed GWL data

Figure 2 represents the following findings;

- Simulated GWL from two models show a good match with observed data and each other
- In some cases MIKE SHE model faces initialization problem, it takes time to match with observed data, but MODFLOW does not face that problem as MODFLOW has already been started with calibrated parameters
- Hydrographs of GWLs show that the maximum and minimum depth to groundwater table occurs at the end of April and at the end of September respectively, that means in the study area, the recharge from rain starts in May and continues up until the end of October-November
- Sometime GWL hydrograph shows variation at peaks. For example, in the Figure 2, overestimated peak in MODFLOW hydrograph represents MIKE SHE provided higher recharge than actual in that place. On the other hand underestimated peak of MODFLOW hydrograph represents MIKESHE provided lower recharge than actual in that place
- Overestimation of drawdown during the dry period is also apparent in GWL hydrograph

Conclusions

Both MIKE SHE and MODFLOW solve groundwater flow problems using finite difference method. However they have some notable differences. The main advantage of the MIKE SHE model over MODFLOW model is that the MIKE SHE model considers all the individual components of hydrologic cycle properly through five basic modules. It incorporates unsaturated zone and overland flow appropriately, so it calculates infiltration, actual evapotranspiration and recharge from their physical laws. MODFLOW, on the other hand, is restricted to simulate groundwater flow only in the saturated groundwater zone. The calculation of unsaturated zone has to do separately before the development of MODFLOW model. Here recharge to groundwater is taken as calibration parameter. Besides MIKE SHE model includes snowmelt but MODFLOW does not incorporate. On the other hand MODFLOW model has some advantages over MIKE SHE model like it has an auto calibration facility, less data is required for model development, less operating time is required, easy to learn by the user's manual, rectangular grid size is allowed, finer model grid is possible for a specific area of interest, etc.

Therefore it is apparent that for simple groundwater flow problem where irrigation is not present, MODFLOW is more suitable. In irrigated area, if recharge is calculated properly from other source, then MODFLOW can be used. For research purpose students will get it as more user friendly.

In the case of groundwater flow study in agricultural purpose where detail calculation of all hydrological components is required, MIKE SHE will be more appropriate.

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