Processing Modflow as a Tool for Groundwater Modeling to Simulate Groundwater Flow and Solute Transport

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Abstract. Water is the most important element essential for healthy society and sustainable development and also to the social and economic infrastructure. With the ever increase in density of population, fast urbanization, industrialization and agricultural use, the demand of water is increasing day by day. As a result, surface water and ground water level is decreasing. Pollution has made good quality water scarcer and more expensive. Groundwater is the favorable alternative, which is facing threats due to anthropogenic activities in India, which has lead due to deterioration in ground water quality. Ground water models provide a scientific and predictive tool for determining appropriate solutions to the mentioned problems by simulating the groundwater flow and transport model for surface water – ground water interaction, landscape management or impact of new development scenarios. This paper presents an overview of the ground water modeling technique and application of Processing Modflow a simulation system for modeling groundwater flow and pollution.

Keywords: Solute transport, groundwater flow model, simulation, Processing Modflow.

1. INTRODUCTION

Water is one of the basic requirements of all life on Earth. Ground water systems are affected by natural processes and human activity, and require targeted and ongoing management to maintain the condition of ground water resources within acceptable limits, while providing desired economic and social benefits. Ground water management and policy decisions must be based on knowledge of the past and present behavior of the ground water system, the likely response to future changes and the understanding of the uncertainty in those responses. The possibility of ground water contamination is due to the mixing up of the water with toxic chemicals, fertilizers, waste disposed site and industrial sites. Hence monitoring of ground water quality has become indispensable.

2. FUNDAMENTALS OF GROUNDWATER

Groundwater is water that occurs in pores and fractures in soil and rock below the watertable. Watertable is defined as the level at which the water pressure equals the atmospheric pressure. Watertable can be thought of as a surface at the boundary between the saturated and the unsaturated zone. In the saturated zone, the pores and fractures are filled with water only, whereas in the unsaturated zone, the pores are filled with both water and air. The water in the unsaturated zone is often referred to as soil water. Units that store significant amounts of water and transmit this water relatively easily are called aquifers. Units that offer a high resistance to flow are called aquitards, or confining layers. Aquifers are broadly categorised as being either confined or unconfined. Confined aquifers are bounded at the top by an aquitard. The water level in a well that penetrates a confined aquifer will rise to a level that is higher than the top of the aquifer (Figure 1). If the hydraulic head is so high that the water level rises above the elevation of the land surface, the aquifer is said to be artesian. By measuring the hydraulic head in multiple wells within a confined aquifer and contouring the measured water-level elevations, an approximate piezometric surface is obtained.

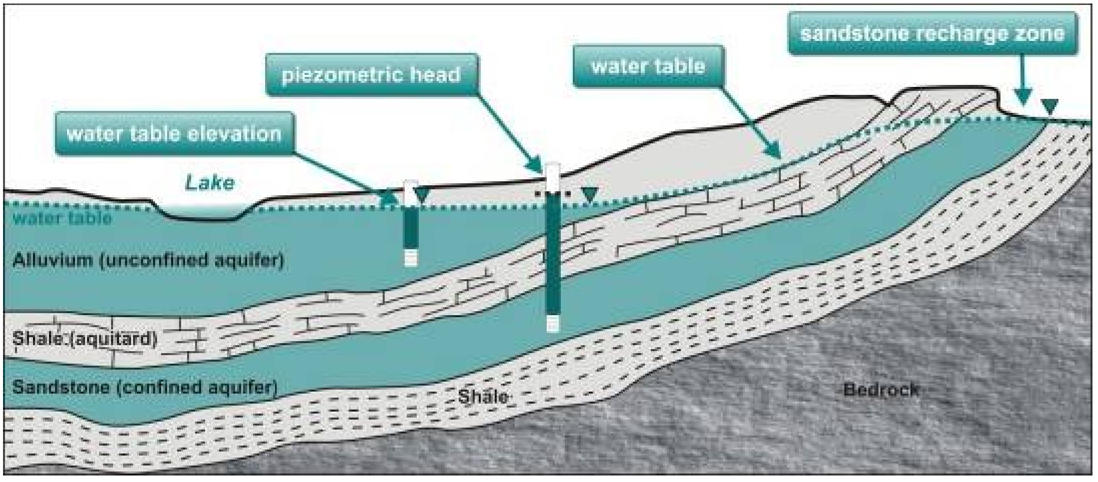

Figure Error! No text of specified style in document.**: A schematic cross-section showing a groundwater system with unconfined and confined aquifers, and connectivity between a surface water body (a lake) and the shallow groundwater.**

Note: The confined aquifer is unconfined in the recharge area. (Figure modified after a version provided by NTEC Environmental Technology)

3. GROUND WATER MODEL

A groundwater model is any computational method that represents an approximation of an underground water system. While groundwater models are, by definition, a simplification of a more complex reality, they have proven to be useful tools over several decades for addressing a range of groundwater problems and supporting the decision-making process.

Groundwater models provide additional insight into the complex system behavior and (when appropriately designed) can assist in developing conceptual understanding. Groundwater models can be used to calculate water and solute fluxes between the groundwater system under consideration and connected source and sink features such as surface water bodies (rivers, lakes), pumping bores and adjacent groundwater reservoirs.

Groundwater models describe groundwater flow, fate and transport processes using mathematical equations that are based on certain simplifying assumptions. These assumptions typically involve the direction of flow, geometry of the aquifer, the heterogeneity or anisotropy of the sediments or bedrock within the aquifer, the contaminant transport mechanisms and chemical reactions.

Groundwater models can be classified as physical or mathematical. A physical model (e.g. a sand tank) replicates physical processes, usually on a smaller scale than encountered in the field. A mathematical model describes the physical processes and boundaries of a groundwater system using one or more governing equations.

A numerical model divides space and/or time into discrete pieces. Features of the governing equations and boundary conditions (e.g. aquifer geometry, hydro-geologogical properties, pumping rates or sources of solute) can be specified as varying over space and time. Numerical models are usually solved by a computer and are usually more computationally demanding than analytical models.

4. GOVERNING EQUATION ON GROUNDWATER QUALITY MODELING

General mass balance equation

The equation governing the movement of dissolved constituents in ground water due to advection and dispersion can be developed by utilizing a conservation of mass approach and employing Fick's law of dispersion. The mass balance of pollutant transport can be stated as,

$$\sum I + \sum P - \sum O - \sum L = \sum A \quad \dots \qquad (1)$$

Where I = input, P = production, O = output, L = loss, A = accumulation.

Flow Equation

Modeling is translating the physical system into mathematical terms. The governing flow equation for three-dimensional saturated flow in saturated porous media is:

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right) \pm Q = Ss\frac{\partial h}{\partial t} \quad \dots\dots \qquad (2)$$

Where,

Kx, Ky, Kz = hydraulic conductivity along the x, y, z axis which are assumed, m/sec (LT^{-1})

h = piezometric head, m (L)

Q = volumetric flux per unit volume representing source / sink terms, T^{-1}

Ss = specific storage coefficient defined as the volume of water released from storage per unit change in head per unit volume of porous material, L^{1}

t = Time, (s) T

Solute Transport Equation

Solutes in groundwater are generally transported by flow. This process is termed advection (or sometimes, convection). Besides being carried by groundwater flow, solutes move from regions of high solute concentration to regions of low solute concentration in a process known as diffusion. Even if there is no groundwater flow, solutes are transported through a groundwater system if spatial concentration differences exist.

The equation represents the movement of flux of solute mass through a control volume. The equation states that the sum of all mass, which consumes or creates solute with the control volume, must be equal to a change in the concentration of the solute with the control volume.

$$\frac{\partial C}{\partial x} = \left[\frac{\partial}{\partial x}\left(Dx\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(Dy\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(Dz\frac{\partial C}{\partial z}\right)\right] - \left[\frac{\partial}{\partial x}(VxC) + \frac{\partial}{\partial y}(VyC) + \frac{\partial}{\partial z}(VzC)\right] \quad \ldots (3)$$

Where,

Vx, Vy, Vz = Seepage velocities in x, y, z directions, m/s (LT^{-1})

Dx, Dy, Dz = Dispersion coefficients, M^2/sec (L^2T^{-1})

C = Solute concentration, mg/m 3 (ML^{-3})

t = Time, (s) T

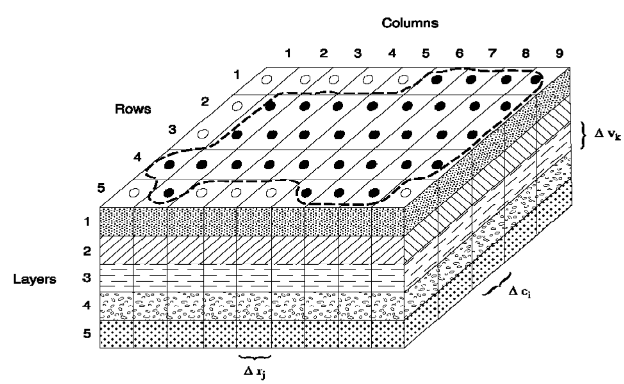

Figure 2: Modflow 3-D grid

Figure 2 presents a sample of MODFLOW three-dimensional grid. The flow region is subdivided into blocks in which the medium properties are assumed to be uniform. In plan view, the blocks are made from a grid of mutually perpendicular lines that may be variably spaced. A flow equation is written for each block, called a cell.

Groundwater Modeling Process

Groundwater modeling process consists of progression through a series of interdependent stages with frequent feedback loops to earlier stages. Figure: 3 illustrates the process.

The planning stage: Here the modelers and key stakeholders should agree on various aspects of the model and the process leading to its development. The process should document the agreed modeling objectives and the model's intended use in contributing to or providing certain outcomes required by the larger project.

Conceptualisation: It involves identifying and describing the processes that control or influence the movement and storage of groundwater and solutes in the hydro geological system.

The design and construction stage: It involves a series of decisions on how to best implement the conceptualisation in a mathematical and numerical modelling environment.

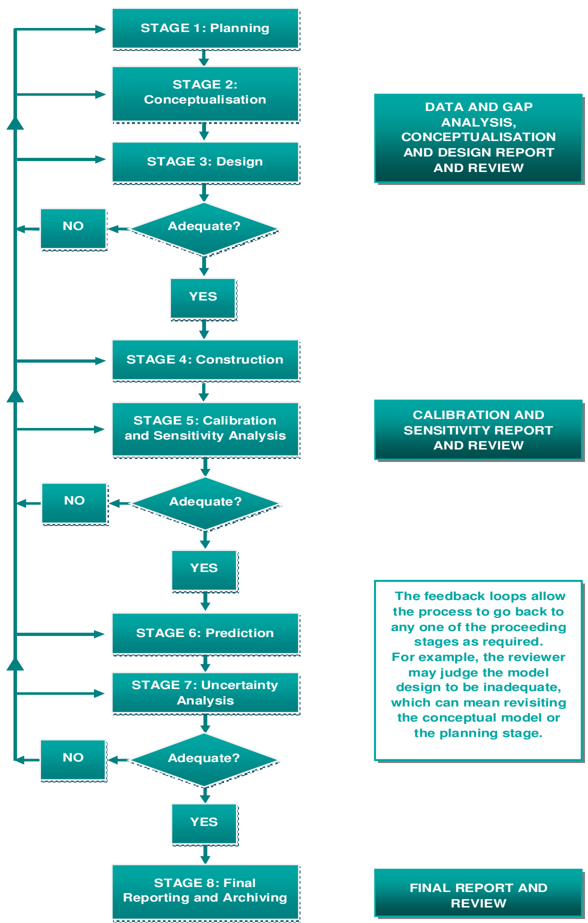

Figure: 3: Groundwater modelling process (modified after MDBC 2001 and Yan et al. 2010)

Model calibration: It involves an iterative process to estimate parameters describing hydro geological properties and boundary conditions so that the model's results closely match historical observations. A balance is needed between simplicity and complexity.

Predictive scenarios: They are designed to answer the questions posed in the modelling objectives. They are run with various levels of applied stresses that represent anticipated changes from the implementation of the project.

Uncertainty: Presentation of uncertainty results, regardless of the methods used, should include a visual depiction that the model prediction is more than a single result or set of results.

Model reporting and Review: The report should describe the model, all data collected and information created through the modelling process. Model review process should be undertaken in a staged approach, with separate reviews taking place after each reporting milestone.

5. PROCESSING MODFLOW

Processing Modflow is a simulation system for modeling groundwater flow and pollution. Processing Modflow was originally developed for a remediation project of a disposal site in the coastal region of northern Germany. It is an integrated modeling environment for MODFLOW, MODPATH, MT3D. It allows to graphical design the model grid, properties and boundary conditions, visualize the model input parameters in two or three dimensions, run the groundwater flow, pathline and contaminant transport simulations.

The modeling tools in Processing Modflow include a Presentation tool, a Result Extractor, a Field Interpolator, a Field Generator, a Water Budget Calculator and a Graph Viewer. The Result Extractor allows the user to extract simulation results from any period to a spread sheet. The results can be reviewed or save them in ASCII or SURFER-compatible data files. Simulation results include hydraulic heads, drawdowns, cell-by-cell flow terms, compaction, subsidence, Darcy velocities, concentrations and mass terms. The Field Interpolator takes measurement data and interpolates the data to each model cell. The model grid can be irregularly spaced. The Water Budget Calculator not only calculates the budget of user-specified zones but also the exchange of flows between such zones. This facility is very useful in many practical cases. It allows the user to determine the flow through a particular boundary. The Field Generator generates fields with heterogeneously distributed transmissivity or hydraulic conductivity values. It allows the user to statistically simulate effects and influences of unknown small-scale heterogeneities. The Field Generator is based on Mejía's (1974) algorithm. The Graph Viewer displays temporal development curves of simulation results including hydraulic heads, drawdowns, subsidence, compaction and concentrations.

Using the Presentation tool, labelled contour maps of input data and simulation results can be created. Colors can be filled to model cells containing different values and report-quality graphics may be saved to a wide variety of file formats, including SURFER, DXF, HPGL and BMP (Windows Bitmap). The presentation tool can even create and display two dimensional animation sequences using the simulation results.

6. CONCLUSION

A ground water model is a simplified representation of a ground water system. Ground water models have proven to be useful tools over several decades for addressing a range of ground water problems and supporting the decision-making process. Ground water models have proven to be useful tools over several decades for addressing a range of ground water problems and supporting the decision-making process. By taking into consideration the basic guidelines of the ground water model, appropriate groundwater models can be developed using Processing Modflow software as a tool to solve various ground water problems such as

1. **Water resource management model:** To provide quantitative estimates of drawdown, loss of baseflow and reduction in water availability to groundwater dependent ecosystems for various levels of groundwater extraction and future climate assumptions.

2. **Mine-dewatering model:** To determine optimum groundwater pumping (including the rate, the number of bores and their location) required to dewater an open-pit mine.

3. **Tunnel construction and operation:** To provide quantitative estimates of the groundwater inflows and associated drawdown during the construction and operation of a new tunnel.

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