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GROUNDWATER MODELING AT A GLANCE

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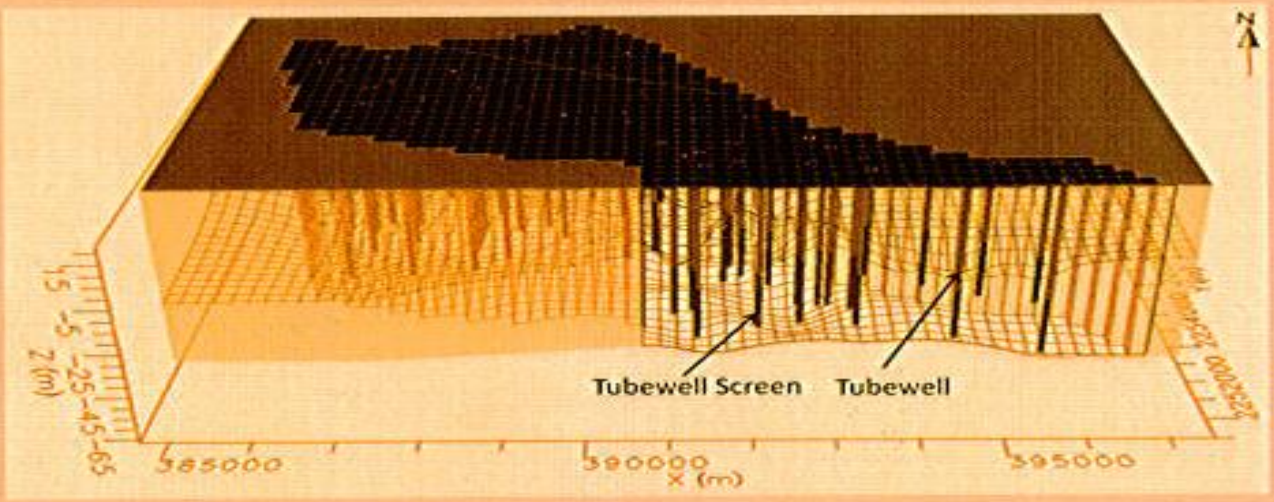

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2015

1. Introduction

Groundwater is one of the most valuable natural resources and it has become a dependable source of water in all climatic regions of the world. It is renewable but finite resource, which is generally characterized by stable temperature and chemical composition. Its unique qualities that it is generally free from pathogens, easily accessible and free from suspended particles has made it the most important and preferred source of water for agricultural and domestic uses. It is estimated that groundwater provides about 50% of the current global domestic water supply, 40% of the industrial supply, and 20% of water use in irrigated agriculture. However, the aquifer depletion due to over-exploitation and the growing pollution of groundwater are threatening our sustainable water supply and ecosystems. In India, in spite of favorable national scenario on the availability of groundwater, there are several areas of the country that face water scarcity due to over-exploitation of groundwater. Excessive groundwater exploitation has led to alarming decrease in groundwater levels in several parts of the country such as Tamil Nadu, Gujarat, Rajasthan, Punjab and Haryana. Therefore, efficient and judicious utilization of groundwater resources is essential as part of sustainable land and water management strategies.

The groundwater simulation models have emerged as a preferred tool among water resources researchers and managers for studying the impacts of groundwater development on future scenario. These models are useful in simulating groundwater flow scenarios under different management options, and thereby taking corrective measures for the efficient utilization of water resources. The simulation approach attempts to replicate real world complexity by integrating components of the physical hydrogeologic system and providing insight into changes within the aquifer and their interaction with overlying surface water systems. Visual MODFLOW is a widely applied groundwater model used by various regulatory agencies, universities, consultants and industry both in developed and developing countries. It integrates the MODFLOW for simulating the flow, MODPATH for calculating advective flow pathlines, MT3D/RT3D for simulating transport and SEAWAT for simulating coupled flow and transport processes. MODFLOW is a modular three-dimensional finite difference groundwater flow model, which simulates transient/steady groundwater flow in complex hydraulic conditions with various natural hydrological processes and/or artificial activities and can be used for large areal extent and for multi-aquifer modeling.

2. Concept of Modeling

A model is a tool designed to represent a simplified version of reality. It is a representation of a portion of the natural or human-constructed world. It is always simpler than the prototype system and can reproduce some but not all of its characteristics. Models can be used as a predictive tool, interpretive tool or generic tool. Different types of hydrologic/hydrogeologic models can be broadly classified into two major groups: material models and mathematical models. Material models can be either physical, scaled-down versions of a real system or analog, which use substances other than those in a real system. Mathematical models are abstractions that represent processes as equations, physical properties as constants or coefficients in the equations, and measures of state in the system as variables. Mathematical models can be either empirical (black box) or theoretical and can be further classified as deterministic and stochastic. Theoretical models rely on physical laws and theoretical principles, whereas empirical models are based on observed input-output relationships only. Deterministic models mathematically characterize a system and give the same response or results for the same input data. Conversely, stochastic models use the statistical characteristics of hydrologic or hydrogeologic phenomena to predict possible outcomes.

3. Development of Groundwater Flow Model

A groundwater model can be defined as simplified representation of real world groundwater systems. The major goal of groundwater modeling is to predict hydraulic head in an aquifer system and/or the concentration distribution of a particular chemical in the aquifer in time and space. Numerical modeling of groundwater systems has been evolving since the mid-1960s and today computer simulation models and interactive computer programs (called "modeling systems", i.e., generalized software packages) are also available. The tremendous advances in computer technology have made them the primary and standard tool for analysis and decision making in small-scale as well as large-scale groundwater problems related to quantity (groundwater flow) and quality (contaminant transport). The dominance of numerical models in groundwater studies has led to the use of phrase "groundwater models" as a synonym for 'numerical groundwater models'. The different steps of numerical groundwater modeling are discussed below.

3.1 Development of conceptual model

A key step in groundwater modeling procedure is to develop a conceptual model of the system being modeled. A conceptual model is a pictorial representation of the groundwater flow system, frequently in the form of a cross-section. The nature of the conceptual model determines the dimensions of the numerical model and the design of the grid. The purpose of building a conceptual model is to simplify the complex field problem and organize the associated field data to make it more amenable to modeling. Simplification is necessary as a complete reconstruction of the field system is not feasible. The analysis of lithologic data collected across the study area will be useful for building the conceptual model. Based on the conceptual model, the governing equation of the model is decided. A conceptual model developed by the authors in their study for the Kathajodi-Surua Inter-basin in Odisha is presented in Fg.1

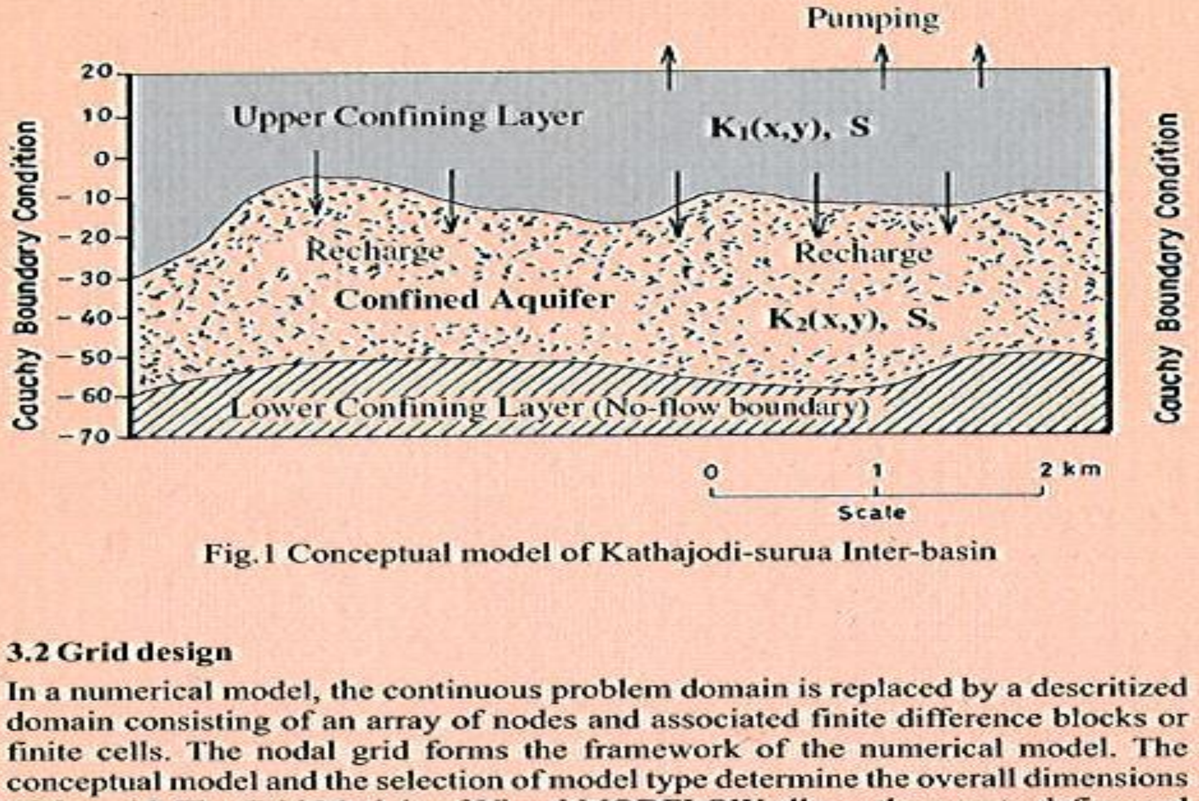

Fig.1 Conceptual model of Kathajodi-surua Inter-basin

3.2 Grid design

In a numerical model, the continuous problem domain is replaced by a descritized domain consisting of an array of nodes and associated finite difference blocks or finite cells. The nodal grid forms the framework of the numerical model. The conceptual model and the selection of model type determine the overall dimensions of the grid. The Grid Module of Visual MODFLOW allows the user to define and discretize the model domain. The user can design a suitable grid, add or delete grid lines, change cell or layer elevations or remove cells from the computations. The grid cells outside the model boundaries can be designated as inactive or no flow cells. These inactive grid cells are ignored by the model and are not used in any of the calculations of flow or contaminant transport. A scale of 500 m length on the field with respect to the dimension of a single grid is quite reasonable in groundwater modeling studies. The model layers are decided based on the conceptual model of the study area. The elevation of the top and bottom of different layers can be assigned by importing them to the model from a MS-Excel database. Similarly, the location of the pumping wells, observation wells and weekly groundwater levels can be imported to the model from Ms-Excel databases. Fig.2 shows the finite difference grid design of the Kathajodi-Surua Inter-basin along with the boundary conditions and pumping nodes.

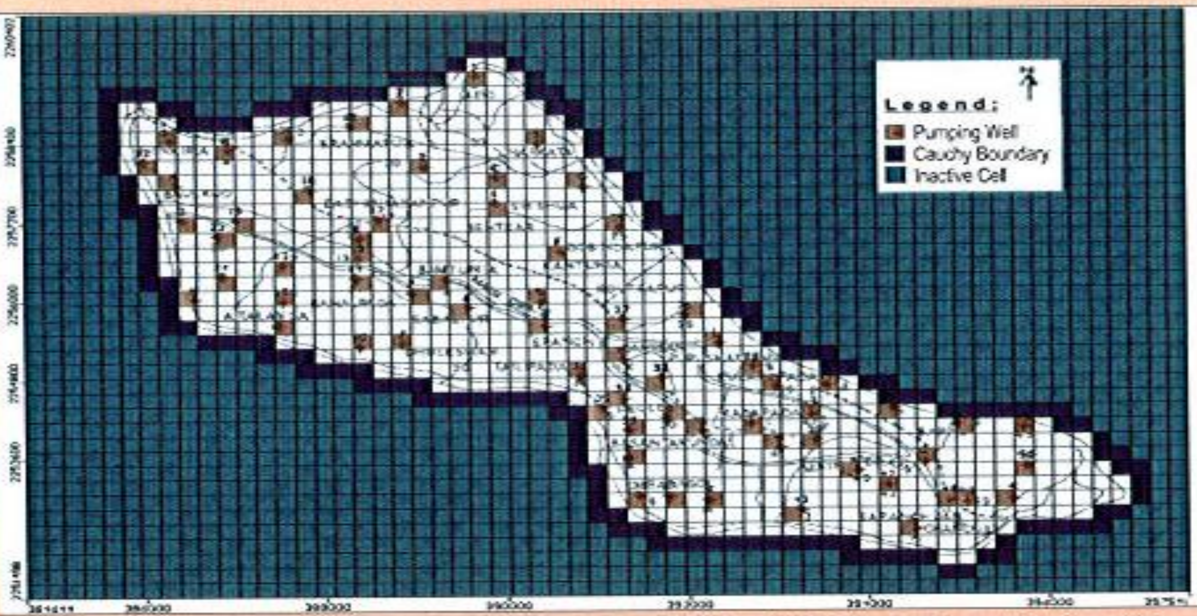

Fig. 2: Design of finite difference grid of Kathajodi-Surua Inter-basin with boundary conditions and location of pumping nodes

3.3 Assignment of boundary and initial conditions

Correct selection of boundary conditions is a critical step in model design. In steady state conditions, the boundaries largely determine the flow pattern. Boundary conditions influence transient solutions when the effects of the transient stress reaches the boundary. Setting boundary conditions is the step in model design which is sometimes subjected to serious error. The boundaries can be physical boundaries or hydraulic boundaries. For example, the groundwater divide and the streamline boundaries are hydraulic boundaries, but the river is a physical boundary. The hydrogeologic boundaries can be of three basic types: (a) Specified head boundaries (Dirichlet boundary conditions), (b) Specified flux boundaries (Neumann boundary conditions) and (c) Head dependant flux boundaries (Cauchy boundary conditions). MODFLOW has separate subroutines or packages to handle boundary conditions such as constant head, river, stream, drain, evapotranspiration and recharge, etc.

Initial conditions refer to the head distribution everywhere in the system at the beginning of the simulation and thus are boundary conditions in time. It is a standard practice to select as the initial condition a steady state head solution generated by a calibrated model.

3.4 Model parameters

The numerical model requires assignment of model parameters like aquifer properties, sources and sinks, groundwater level distribution and spatial and temporal distribution of recharge, evapotranspiration etc. The aquifer parameters mostly include hydraulic conductivity and specific storage in case of confined aquifer and specific yield in case of unconfined aquifer. The pumping test analysis is the most ideal method of estimation of model parameters on a regional scale. In case of absence of pumping test data, grain size analysis and textural information can be used for estimation of model parameters like hydraulic conductivity and specific storage. However, as the estimation of aquifer parameters can not be guaranteed to be cent per cent accurate, further refinement in their values can be done during the course of calibration. It is a standard practice in groundwater modeling that whenever only horizontal hydraulic conductivity data is available, the Kh to Kv ratio is assumed as 10 for alluvial aquifer systems.

The Well Package of MODFLOW software is designed to simulate inflows and outflows through recharge wells and pumping wells, respectively. The location of the pumping and observation wells can be imported, added or deleted using this package. Well-screen intervals, pumping schedules and observed groundwater head data can be provided to each pumping well either by direct assigning or importing them from MS-Excel files. The day-wise pumping extraction data is generally not recorded in developing countries like India. Therefore, questionnaire survey of farmers can be done to obtain historical record of pumping data. The agricultural crop coverage and electric consumption can be used as indirect indicators for obtaining pumping extraction data. Recharge is another input parameter to the model which needs to be estimated. Recharge package of MODFLOW is designed for zone wise and layer wise assignment of the parameter. No single recharge estimation method can be guaranteed to be cent per cent accurate. Therefore, two or three different methods should be used before arriving at a recharge value. Simplest method of recharge estimation is the empirical methods with respect to the monsoon rainfall. Further refinement of the recharge value can be done during the calibration of the model. Evapotranspiration is another input parameter to the model which can be estimated from the land use map and crop coverage of the study area.

3.5 Model calibration

Calibration of the numerical model refers to the demonstration that the model is capable of producing field measured heads and flows. Calibration is accomplished by estimating a set of parameters, boundary conditions, and stresses that produce simulated heads and fluxes that match field-measured values within a pre-established range of error (known as 'calibration target'). Analysis of the difference between observed and simulated heads gives an indication as to where adjustment of calibration parameters may be necessary in order to minimize the difference. Finding this set of values amount to solving what is known as the inverse problem. Generally, hydraulic conductivity, specific storage and recharge are considered as calibrated parameters for groundwater flow simulation models. Model calibration can be performed using steady state or transient data sets. Most calibrations are performed under steady state conditions, which may also involve a second calibration to a transient data set. After the calibration, the model is validated using another set of data. There are basically two ways of finding model parameters to achieve calibration, i.e., of solving the inverse problem: trial and error calibration (also known as 'manual calibration') and automated calibration.

In the trial-and-error calibration, parameter values are initially assigned to each node or element in the grid. During calibration, parameter values are adjusted in sequential model runs to match simulated heads and flows to the calibration targets. This method is generally very time consuming, cumbersome and influenced by modeler's expertise. Automated inverse modeling is performed using specially developed codes that use either a direct or indirect approach to solve the inverse problem. An inverse code automatically checks the head solution and adjusts parameters in a systematic way in order to minimize an objective function, an example of which would be to minimize the sum of the squared residuals, i.e., differences between simulated and observed heads. The automated inverse modeling may not be subjective and is not influenced by the modeler. However, it suffers from being complicated and computer intensive.

3.6 Performance evaluation of the model

In groundwater modelling studies, different criteria of evaluation like correlation coefficient (r), mean absolute error (MAE), root mean squared error (RMSE) and Nash-Sutcliffe efficiency (NSE) are generally used during calibration process. Mean absolute error measures the average magnitude of the residuals, and therefore provides a better indication of calibration than the mean error. Correlation coefficient determines whether two ranges of data move together, i.e., whether large values of one data set are associated with large values of the other data set, whether small values of one data set are associated with large values of the other data set, or whether values in both data sets are unrelated. The root mean squared error is a widely accepted performance evaluation index and performs very well if the errors are normally distributed. The Nash-Sutcliffe efficiency is another widely used performance evaluation index for hydrological models. The best-fit between observed and simulated groundwater levels under ideal conditions would yield MAE = 0, RMSE = 0, $r = 1$ and NSE = 1.

3.7 Sensitivity analysis

Sensitivity analysis is another component of model evaluation, which addresses uncertainty in modeling results. Due to the uncertainties in estimating aquifer parameters, stresses and boundary conditions, a sensitivity analysis is an essential step in modeling studies. This is particularly important when many parameters are to be optimized during calibration. The main objective of a sensitivity analysis is to understand the influence of various model parameters and hydrological stresses on the aquifer system and to identify the most sensible parameter(s), which will need a special attention in future studies. Sensitivity analysis is also simultaneously done during the calibration of the model. Hydraulic conductivity and recharge are generally found to be more sensitive and specific storage or storage coefficient is normally a less sensitive parameter.

3.8 Simulation of groundwater management scenarios

The calibrated and validated model can be used for a variety of management and planning studies. In a predictive simulation, the parameters optimized during calibration are used to predict the system response to future events. Different type of predictive simulation can be done to study the response of the aquifer to different management scenarios. This may include response of the aquifer to different pumping levels and to simulate groundwater levels in the long run under existing or different management options. Based on the results of this study, management strategies could be formulated for the efficient utilization of water and land resources in the study area.

4. Data Required for Groundwater Modeling

1. Base map of the study area.
2. Groundwater level data: water table/piezometric level depth or elevation (spatial: at multiple sites, and temporal: hourly/daily/weekly/monthly for several years).
3. Water table/piezometric level contour maps for wet and dry periods.
4. Groundwater pumping rates of the existing production wells.
5. Groundwater consumption in various sectors (past and present); and total water demands.
6. Rainfall data at a suitable site (daily/hourly) for several years.
7. Natural recharge data (spatial and temporal, if any), and artificial recharge data (if any).
8. Geological data/lithological information (well-log details at multiple sites, preferably grid-wise or section-wise over the area).
9. Hydraulic conductivity/Transmissivity and storage coefficient/specific yield data (point values and areal distribution) for aquifer systems, and vadose zone system (if necessary).
10. Pumping-test/slug-test data at multiple sites.
11. River (s) stage and/or discharge data (temporal: daily/hourly or monthly, and spatial: at various locations along the river reach). Also, river-bed elevation data along the reach.
12. Canal discharge and operation data/information.
13. Surface water and/or groundwater quality data (spatial and temporal).
14. Landuse/Land Cover map and Soil Map or information.
15. Topographic map with complete descriptions of streams/stream network, canal network, and other water bodies.

Published by : **Director, ICAR-Indian Institute of Water Management**
Bhubaneswar- 751 023
Printed by : **S J Technotrade (P) Ltd.**
Subarnarekha Chambers, Plot No : A-9 & 10, Unit - IV,
Bhouma Nagar, Bhubaneswar -751001
E-Mail : info.mailtechnotrade@gmail.com, Cell: 9132573795