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APPLYING MODELING TECHNIQUES TO MANAGE GROUNDWATER RESOURCES

Upma Shama*[1], and Mahesh Kothari[2]

ABSTRACT

The present paper perusals current status of groundwater resources of India. Available groundwater resources are used for various purposes like drinking, irrigating etc. Description of different aspects of groundwater resources like sub surface distribution of water, geologic formations of groundwater, aquifer types, investigation of ground water development etc have been discussed. In most of the region of India, this resource has been misused and overexploited causing its depletion since last few decades. Being the only resource of agriculture during non-rainy season, its adequate and efficient utilization is a subject of concern. Hence the study will present modeling approach for analyzing groundwater resource and offer various options for its proficient and suitable utilization for irrigation. Groundwater models aimed at describing the behavior of groundwater system. These models are useful for purposes like predicting aquifer response for external changes like external changes like extraction and recharge, movement of contaminants within the aquifer system etc. these models are also useful as management tools as several management alternatives like number and spacing of wells and their effect on water table, effect of location and quantity of recharge, etc. can be analyzed. All the models available for groundwater flow management like physical, analogue and mathematical models have been reviewed and compared to propose the optimal approach for its apt utilization.

Keywords: *Numerical simulation, coastal aquifer, Seawater intrusion, pumping, SEAWAT, interface*

INTRODUCTION

Groundwater is one vital available stored water source used for drinking, irrigation and commercial purposes in the world, because of its freshness, chemical compositions, constant temperature and less pollution (M. Rajasekhar et al. 2022) At present, globally around 34% of the available water resources is groundwater in both rural and urban area (Kadam et al. 2021a, b; Gaikwad et al. 2021). Most of the world's area comes under arid and semi-arid region with irregularities in rainfall pattern, hence average precipitation is less than one third of the world's average rainfall (Pinto et al. 2017). Around 2/3rd of global population lives in water scarce conditions for at least a month per year revealed in recent research. And about 50% of the above population lives in India and China (UN-Water 2017). Although annual rainfall in India is quite plenty around $4000*10^9$ m^3 while 1/4th ($1123*10^9$ m^3) of the total is useful. In 1992, Falkenmark and Widstrand, stated that a country faces consistent and long lasting water scarcity when the renewable water deliveries fall below 1700 m and 1000 m per capita per year. As per report of Ministry of Water Resources (2015), in India per capita average available water is 1816 m in 2001 which is expected to decrease to 1140 m till 2050. In past few years, groundwater resources have progressively developed as the strength of irrigation and drinking water safety in India by meeting increasing water demand (Vijay Shankar et al. 2011). Saha and Ray (2018) reported currently groundwater contributes about 62% in irrigation, 85% in rural and 45% in urban water delivery.

This situation has created water stress condition in several parts of the country. This dependency need a complete comprehensive study of the valuable natural resource for its efficient management in a justifiable way.

Hence, for groundwater investigation, conservative geophysical methods and tedious soil tests are quite expensive and onerous (Ghosh et al. 2020; Moustafa 2017; Chandra 2016; Mukherjee et al. 2012). On the contrary, RS and GIS have emerged as efficient tools for successfully performing complicated groundwater studies like demarcation of groundwater pattern with ease (Kadam et al. 2019; Shailaja et al. 2019). Remote sensing briefly describes high resolution thematic images for groundwater resources (Kaliraj et al. 2014; Javed and Wani 2009). Groundwater modelling with geospatial approach has an additional benefit over conventional methods as a range of constraints can be represented on a single map (Kumar et al. 2020; Machireddy 2019; Nithya et al. 2019; Magesh et al. 2011). Several decision-making methods in combination with RS and GIS in various studies proposes execution of actual outcomes in groundwater resources evaluation (Rajasekhar et al. 2022).

Groundwater resources in India

In 2020, the total groundwater recharge and total natural discharges for the whole country has been evaluated as 436.15 bcm (Billion Cubic meter) and 38.51 bcm (Billion Cubic Meter) as per CGWC report. As a result, annual extractable groundwater resources for the country is calculated as 397.62 bcm. Out of the total groundwater recharge around 57 % (249.65 bcm) occurs

1. *Junior Engineer, CAD, Kota-324009, Rajasthan, India*
   **Corresponding Author, E-mail:.drmkothari@hotmail.com*
2. *Professor and Head , Department of Soil and Water Engineering, College of Technology and Engineering, MPUAT, Udaipur-313001, Rajasthan, India*

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in the monsoon season. While in states/ UT of Bihar, Goa, Jharkhand, Meghalaya, Kerala, Nagaland, Madhya Pradesh, Gujarat, Mizoram, Manipur, Sikkim, Andaman & Nicobar, Daman & Diu, Dadra & Nagar Haveli and Lakshadweep Both monsoon and non-monsoon rainfall as a whole contributes 64 % of country's total annual groundwater recharge and rest i.e. 36 % is recharged from other sources like recharge from tanks, ponds and water conservation structures, canal seepage and return flow from irrigation.

On comparing annual groundwater recharge estimates of the entire country in year 2017 and 2020 an increase of 4 bcm has been observed. Assessment has shown an increase (5 bcm) in annual extractable ground water resources while a decrease (4 bcm) in annual ground water extraction for domestic, industrial and irrigation purposes. This is due to the alterations of parameters, alterations in well census data and varying ground water system.

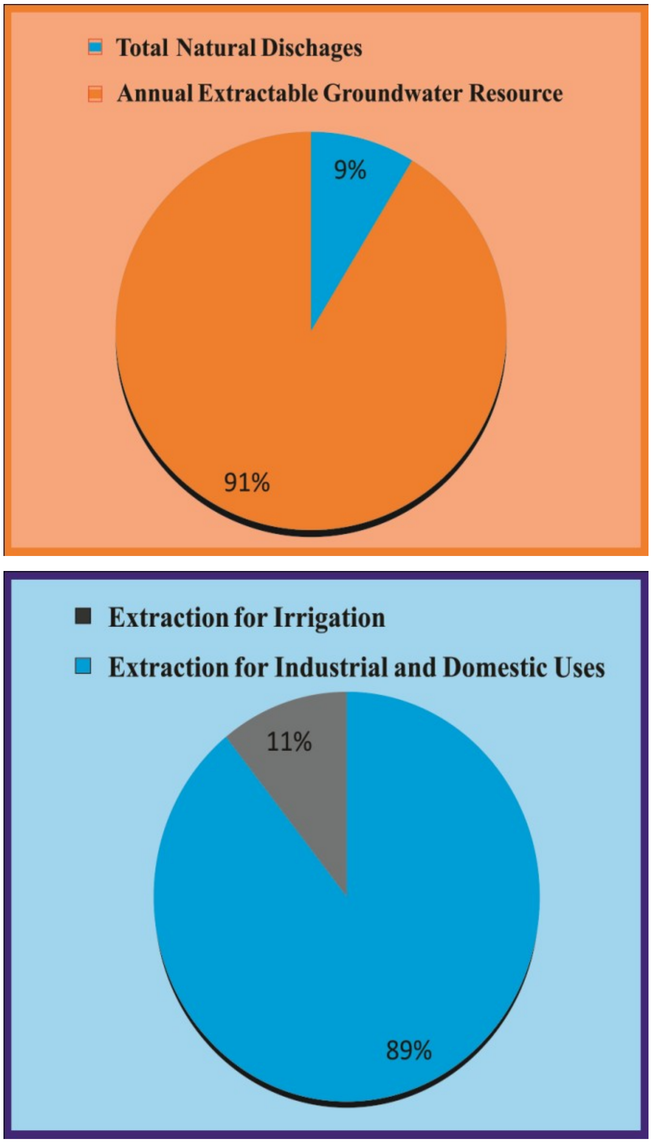

Fig.1: Ground Water Resources and Extraction Scenario in India, 2020

Groundwater occurrence and movement

A study of occurrence and movement of groundwater is needed for the location of wells, their design and in the overall movement of groundwater resources. Groundwater studies are also required in the design of foundation of hydraulic structures and in assessing returns flows to rivers.

Subsurface distribution of water

The occurrence of water below the land surface can be divide into two zones that is the saturation zone and the aeration zone. In the saturation zone, all the pores are entirely filled or saturated with water. Bottom of the saturation zone is bounded by an impervious strata. While upper surface of the saturation zone (in case of absence of overlying impermeable layer) is called the water table. This water in saturation zone is usually denoted as groundwater.

The aeration zone occurs above saturation zone contains pores partially filled with air or water. This is further divided into three belts, i.e., (i) the soil water belt, (ii) the intermediate belt, and (iii) the capillary fringe. The soil water belt lies immediately below the soil surface and spreads through the root zone of the crops or the other vegetation. From this belt plants extracts the required moisture for their growth.

The capillary fringe lies instantly above saturation zone where water is deferred by capillary forces like in a capillary tube. Capillary fringe thickness depends upon the soil texture. More narrow are the pores more is the rise in water. The intermediate belt occurs between the two belts and connects both these zones. Excess water in this region flow downward due to gravitational force.

Geologic formations for groundwater supply

Geologists describe all earth materials as rocks. These are of two types: (1) the consolidated type, where particles are held decisively by compaction and cementation (examples are granite, sandstone, limestone), and (2) the unconsolidated type, i.e. loose material (examples are clay, sand and gravel).

All geologic formations although contains water but may not produce enough water for the wells purpose. Therefore, those yield significant amount of water are known as aquifers. Gravel are the best among all types of rocks or subsoil. After gravel in yielding water are aquifers consists of sand, sandstone and limestone. Clays and fine silts are most unproductive materials. Granite with strong joints, fissures and faults produce sufficient amount of water. Porosity and permeability (openings must be interconnected to permit the travel of water through them) are the two properties of the aquifer material which makes it good in yielding water.

Types of Aquifers

Aquifers may be classified as confined, unconfined and semi confined. An unconfined aquifer also called water table aquifer is defined as an aquifer which is not confined by an upper impermeable layer where water stays at atmospheric pressure. The upper surface of the saturation zone is know as the water table. When a well is constructed in these aquifers the level of the water table is the level of water in the well. In a confined aquifer, water is confined by an overlying impermeable layer. This is also called an artesian aquifer. Water in these aquifers is under pressure above atmospheric pressure. When well is drilled water rises to a level above the bottom of the upper confining layer because of the pressure under which the water is held. The imaginary level to which water rises in a well located in an artesian aquifer is called piezometric level. The area through which water enters the artesian aquifer is known as the recharge area. A special type of an unconfined aquifer is the perched aquifer which occurs whenever a groundwater body is separated from the main groundwater by a relatively impervious layer of small areal extent. A semi-confined aquifer, also known as a leaky aquifer is a completely saturated aquifer that is bounded above by a semi-permeable stratum. Lowering of the piezometric head in leaky aquifer, by pumping or otherwise, will generate a vertical flow of water from the semi- permeable layer into the pumped aquifer.

Unconfined, confined and leaky aquifers can occur together in a vertical cross-section and in such case referred to as a layered or multiple aquifer.

Investigation for groundwater development

For the exploration of groundwater resources in a given area, a knowledge of occurrence and movement of groundwater is required. In addition, the hydrological parameters of the aquifers are needed to decide the location and types of wells. The geological conditions of the area will influence the occurrence and movement of groundwater. Hydrogeology refers to the study of the laws of occurrence and movement of groundwater, its chemistry and its relation to the environment. Groundwater prospecting and development helps in locating groundwater and understanding some aquifer properties.

Methods for development , of groundwater may be classified as follows:-

1. Surface: Geological field reconnaissance and Geophysical methods.
2. Subsurface: Geophysical methods, Test drilling and Interpretation of well data.

Geological reconnaissance helps in understanding the geology of the area in relation to the possible occurrence of groundwater. A study of structural geology in conjunction with stratigraphy to locate possible water bearing formations is required. Stratigraphy helps in locating the position and thickness of water bearing formations and confining beds. Gravel, sand, sandstone and limestone are best water carries even though all such deposits may not yield significant quantities of water. Clay formations, shales and crystalline rocks does not yield enough water for exploration.

Role of Modelling in Groundwater Management

Groundwater resources occur below the surface with dynamic properties, their quantity and quality both varies at very short distance due to which its measurement at specific point in a specific point of time is quite difficult. The change in the state of hydrogeological system over time is pretty obvious. Hence, many experts and technicians are continually making rigorous efforts to develop new scientific models and solutions to assess these systems. These models help hydrogeologists to extract require information regarding ground water strata, behaviour of the entire system or a part of it, predictions regarding future problems and subsequent actions to manage or control them and test the hypothesis (Figure 1).

Major role that groundwater modeling plays in managing the resources include data analysis and available literature (classification and predictions) which improve hydrogeological know how about the system, simulation (predictions) to assess aquifer pattern, detection of solutions to meet the objectives (designing and construction), optimization to achieve maximum benefit at minimum cost, evaluation of water availability and movement (inflow, outflow and water balance), estimation of already developed conditions of an aquifer system (enhancement and development), predictions of behaviour of groundwater strata under varying hydrogeological stresses (management and decision-making), enumeration of sustainable and safe crop production (water distribution strategies), sensitivity analysis and optimization of sensitive parameters (uncertainty and risk analysis), visualization of system behaviour, development and current & future actions (mapping and illustrations) and interpretation of strong and weak points of other researches and concepts through modeling (learning and teaching).

Groundwater Models Classification

The classification of groundwater models is done on the basis of quality into the board, detailed and detailed together with prediction modeling modules (Middlemis et al. 2001). Firstly, fundamental and cost effective models suitable for standard assessment, partial planning, and data gap detection. As such models do not required much information to develop, hence these are not suitable for analysing complicated conditions. The second type of models are developed by using more details and complex data with better understanding of the groundwater system.

These type of models are used for describing suspected groundwater problems. The third type of models also called aquifer simulators are also precise, time-consuming and expensive. These models can forecast the alterations in groundwater strata and their interfaces with the surface water on a large scale (watershed or aquifer). Outcomes from models can be used for managing and developing complete groundwater system (Payne and Woessner 2010).

Groundwater models can further be classified based on various independent methods. On the basis of the model structure, groundwater models can be normally be classified into three categories which includes physical, analog and mathematical. Mathematical models are of types deterministic and stochastic (statistical) models. The deterministic models further can be classified as analytical or numerical.

Physical Groundwater Models

Physical models also called porous media models or mocked–up models like sand-box, bench-scale, parallel-plate and viscous fluid models are an abstracted and scaled-down laboratory representation of a groundwater system. The initial modeling on groundwater system was performed using physical models that appeared in European literature. The Darcy's experiments (1855) explaining the fluid flow in porous media can be considered as the first works in groundwater modeling (Schweizer 2015; Landmeyer 2011; Simmons 2008).

Physical models have many applications in seepage simulations, artificial restoration, diffusion, and seawater interruption, in conditions that are slightly known regarding development and dynamics of groundwater system. Physical model has one most difficult issue in finding appropriate scale so that actual groundwater system can possibly be represented in most effective manner. Further, only some situations can be explained by these models which are generally associated with hydraulic properties of the porous media. Other limitations related to physical models is its setup is expensive and consumes time. Regardless of all above drawbacks these tools are suitable for practical learning of the basic theories of groundwater hydrology. An explanation of the innovative works regarding numerical modeling of the groundwater in porous media is provided by Pinder and Bredehoeft (1968).

Analog Groundwater Models

Analog models uses the correlation between Darcy's Law and other physics laws like Fourier's law of heat transfer, Navier-Stokes equation of fluid motion, Fick's law of solute diffusion and Ohm's law of electricity to explain the pattern of a groundwater system (Delleur, 2010).

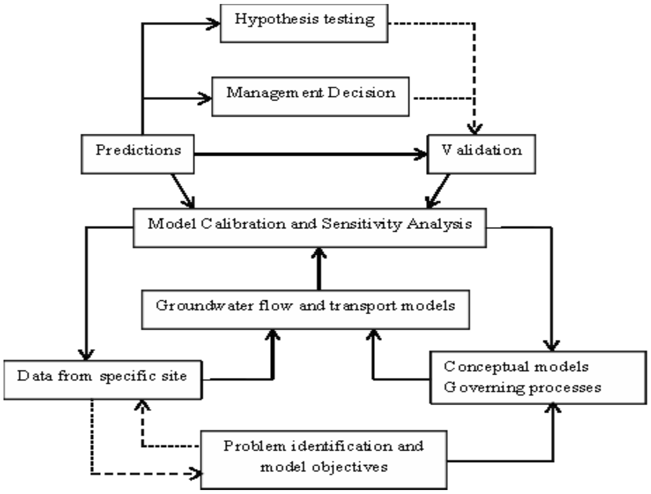

Fig. 1: The development and application of the modeling in the analysis of groundwater problems, decision making, hypothesis testing (referred from Konikow et al. 1996)

Some common systems of analog models for groundwater are electrical, thermal, membrane and thermal models. For instance, an electric analog model performs simulation by considering aquifer storage (capacitance) and groundwater flow (resistance) in which model uses resistors and capacitors network organized in grid for aquifer geometry estimation. Mathematically, flow of water in porous media (Darcy's law) corresponding to the electrical flow in a material conductor (Ohm's law) is given by Thangarajan (2007):

$I=-\sigma\ dVdx$ (Ohm's law) (1)

where I is the electrical current per unit cross-sectional area, σ is the specific electrical conductivity of a substance, and $dVdx$ is the voltage (potential) gradient

$V.\ q=-K\ dhdx$ (Darcy's law) (2)

where I is the Darcy velocity, and is similar to the electrical current stated in equation (1). The hydraulic conductivity K is alike the electrical specific conductivity σ, and hydraulic head h corresponds to the electric potential.

Mathematical Groundwater Models

Mathematical model are designed by using various equations,, parameters and records which can mathematically expresses and denotes groundwater system nature. Groundwater geometry and hydrogeology, spatiotemporal boundary conditions, initial conditions and pressures of the system are considered for framing several equations and related parameters. In Figure 2, a schematic shows the connections between the elements of a simplified solute transport numerical model.

Mathematical models are of two types deterministic and stochastic (statictical) models. Stochastic models are formulated based on statistical parameters like probability of occurrence and spatial variables to attain probably results and solutions. Deterministic models are framed on the basis of the reason and outcome relations (one process, a cause, contributes to the production of another state, an effect) of identified systems and practices. These models distinctively identifies local and regional systems. The solutions of processing equations can be achieved by analytical (in case model is simple), numerical or combination of both approaches.

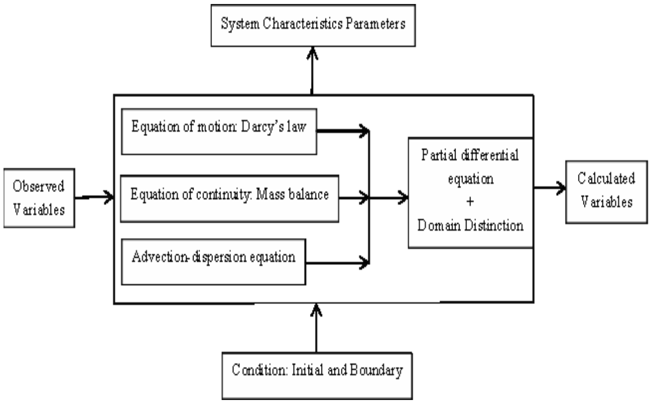

Fig. 2: Schematic representation of simplified solute transport numerical mathematical model

Analytical Groundwater Models

Firstly, Dupuit (1863) used analytical approach to explain the steady flow of groundwater when pumped to wells in confined or unconfined aquifers (Renard, 2005). In 1886, Philipp Forchheimer (an Austrian engineer) had expanded and generalized the above approach. A commonly used solution is The Theis solution (1935) which analytically solves groundwater hydrology considering various aquifer types, flow systems, stresses and boundary conditions. Since years, analytical techniques have been used as an ideal tool for solving the groundwater system dynamics. All these are now sometimes used prior to initiation of a numerical model.

The drawback of these models is that considers some mathematical assumptions which are usually not possible. Also they do not allow simultaneous simulation of spatiotemporal variations in several parameters. Therefore, they are often not suitable to simulate a varied subsurface system closely.

Numerical Models

With the computerization and digitization of technology in late sixties, adaptation of numerical models became common to obtain more inclusive visualization of the complex groundwater system. With the help of numerical model, experts directly estimated solutions to the complex differential equation solutions of the system by changing them to distinct equation thereafter divided the domain into grids or meshes. In these models, division of an area and distinction of differential equations are usually attained by estimation methods like finite element, finite difference and finite volume boundary. Any of these approaches can applied single or in combination with other methods to decrease the complicated computation of numerical models. Accounting application, simplicity in use, performance and formulation speed each approach has its pros and cons. Even after considering all pros and cons, yet, finite element and finite difference methods are specially most preferred methods for groundwater movement and transport equations solution (Wang et al., 2019).

Flow and Solute Transport Models

Above stated classification of groundwater models shows that it certainly has a long history with varied methods. Initially, modeling approach focused on mainly on groundwater quantity characteristics. Groundwater flow models used to regularly estimate the velocity, flow rate and groundwater flow direction both within and across aquifer system boundaries (Mandle, 2002). The groundwater flow model obtains results as groundwater fluxes and hydraulic heads that are in equilibrium with the set physical and hydrogeological conditions for the model. With time, the experts started emphasizing more on quality than quantity in groundwater strata. From the mid-1960s, formulation of groundwater solute transport models was performed for simulation of dispersion and outcome of different chemical classes in various hydrogeological settings. The models could perform well for simulation of groundwater flux and solute concentration regarding the geochemical, spatial temporal and hydrogeological conditions. As the amount of flow, storage and variation in the solute concentration (transformation) are controlled by the velocity of groundwater flow (flow distance for a given time), hence a precise explanation of flow system is vital for simulating solute transport problems.

Usually, the word ―solute transport model‖ is referred for defining models used to simulate the ―movement, storage and transformation‖ of a soluble chemical species (contaminant). As per Bear and Cheng (2016), solute forms a small part of a solvent in a solution. As the best reachable groundwater resources are found alluvial plains, therefore analysis of solute transportation in the porous media are mostly considered. A porous medium is a section in pores consisting minimum of two homogeneous material components, showing detectable boundaries between them at a resolution level, with minimum of one of the component remains fixed or somewhat distorted (Lage and Narasimhan, 2000).

Application of solute transport model

Solute transport modeling in porous media simulates climatological, hydrological, hydrogeological, agricultural, geological, geographical, environmental, hydraulic, industrial, economical and health aspects related to groundwater resources. In hydrogeology, the main purposes of these models are to study the mass balance of chemicals, to understand concentration data, to explain the bulk and large scale movement of chemicals (advection or convection) or random, small scale movement of chemicals (dispersion), to evaluate the mixing or dilution amount parallel (longitudinal diffusion) and perpendicular (transverse diffusion) to the flow path, to form a monitoring plan and risk calculation, to simulate chemical processes and the variation in chemical concentration taking place by suspension, retardation and degradation (e.g., adsorption, precipitation, hydrolysis, cation exchange, bioaccumulation, redox reaction, biodegradation), to assess the cleaning period using rectification strategies, to manage and safeguard quality of groundwater.

Table 1. Simulator software for groundwater flow and transport modeling

Model	Description
MODFLOW	This model simulates water flow in the saturated zone; it can be linked with chemical transport modules and particle tracking modules (for flow path simulations)
MODPATH, path3D	the model is a 3-dimensional particle tracking software for flow path and pattern simulation; the model can be integrated with MODFLOW;
MT3D	MT3D simulates 3-D advection, dispersion, sorption, and reaction; it can be linked to MODFLOW, the model solves equations based on the finite-difference method; it is suitable for both saturated and unsaturated zones.
BIOPLUME 1, 2 ,3	Family of models that couples chemical transport with biodegradation. BIOPLUME 2 focuses the aerobic reactions that occure under oxygen- limiting conditions. BIOPLUME 3 simulates the aerobic and anaerobic reactions with multispecies biodegradation kinetics. The model can be used to simulate the fate and transport of hydrocarbons and electron acceptors.
3DFEMFAT	A 3-Dimensional flow and solute transport model that simulates both saturated and unsaturated media. The solution is based on the finite element method; it is suitable for density-dependent flow and transport.
BIOF&T	A 2- and 3-Dimensional software for both fractured media and porous media; it is suitable for simulation under heterogeneity; the model can consider advection, dispersion, sorption, reaction, and biodegradation.
CHEMFLO	CHEMFLO is a one-dimensional vadose zone screening model; its simulation is based on the finite difference method.
CHEMFLU X	This model is a finite element model useful to solve advection, dispersion, sorption, and decay problems; it has the capability for automatic mesh size and time step refinement.
MOFAT	MOFAT can Simulate the LNAPL movement from the surface spill to the water table.
UTCHEM	This software simulates the movement of air, water, and soil through saturated and unsaturated zones. It can simulate multiphase fluid flow as well as formation in vadose and saturated zones.
FEFLOW	A 2- and 3-D software that is used for both saturated and unsaturated media, the model is suitable for salinity and heat-dependent transport.
FLONET/ TRANS	This model is a 2-D flow and solute transport-retardation model that simulates based on the finite element method.
HST3D	A 3-D groundwater flow and solute transport software that used for a single solute with advection, dispersion, linear sorption, and first-order decay.
MOC	A 2-D finite-difference software that simulates groundwater flow and solute transport under the influence of advection anddispersion, along with first-order decay. This software is also useful to simulate the reversible equilibrium- controlled sorption and reversible equilibrium-controlled ion exchange.
SWMS 2D	A 2-D software that is practical for simulating flow and solute transport in variably saturated media with irregular boundaries under the influence of dispersion, linear sorption, zero-order production, and first-order decay.
VSAFT2	A 2- and 3-Dimensional software for both fractured media and porous media; it is suitable for simulation under heterogeneity; the model can consider advection, dispersion, sorption, reaction, and biodegradation.
SUTRA	CHEMFLO is a one-dimensional vadose zone screening model; its simulation is based on the finite difference method.

CONCLUSION

Groundwater modeling is dominant and prevailing tool for both qualitative and quantitative analysis of groundwater resources over time. On comparing several models, numerical models are found quite flexible, reliable and practical in solving complex groundwater system problems which do not have easy and direct solutions. In such situation, choosing a model intricacy that regulates the performance of a numerical model is quite challenging. The execution of numerical model for groundwater system analysis depends upon several conditions like characteristics of theoretical model, its structure, input data quality, solution methodology, features of modeling area (spatiotemporal resolutions), expert efficiency etc. A comparison with flow models shows that the of solute transport models performance can be affected by additional factors like domain size, density and viscosity alterations, variations in hydrological stresses (e.g., groundwater extraction from wells and surface recharge), heterogeneous behaviour of the medium, chemical and physical properties of solute and complicated chemical processes happening in the groundwater zone. While solute transport models mostly solves 1 or 2-D transport of a single, non-reactive solute, in homogenous and isotropic conditions, in a steady-state regime, but the modified and improved versions can solve complicated problems, both one or multi-dimensional which involves multiple chemical classes, varied carrying practices, medium heterogeneity, complex boundary conditions and time-changing stresses. There is still need of more studies, research and computations to improve their performance and reduce ambiguities in the outcomes

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