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Groundwater Modelling using Visual MODFLOW in the Last Two Decades in India: A Review

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Abstract: ***Owing to the rise in groundwater demand and looming the depleting groundwater level and its deterioration, recent years have witnessed much focus on groundwater flow and pollutant migration modelling using Visual Modflow. It is a Graphical User Interface (GUI) for the USGS MODFLOW which becomes a commercial software and most popular among the groundwater modellers for its user-friendly features. For sustainable management of groundwater resources, groundwater regenerative model is the best characterized by multiple inputs and output stresses acting on the aquifer system. This MODFLOW is mainly used for groundwater flow and pollutant transport model under the diverse hydrogeological and meteorological conditions. Beginning with a discussion of Visual Modflow applications, this paper attempts to provide a review of the versatility of its applications in groundwater modelling for the last two decades in India. The scientific areas are such as agriculture, river-aquifer interaction, demarcating groundwater protection zones, assessing of waterlogged area, constructed wetlands, pollutant migration, landfills, mining operations, seepages of railway tunnels, construction of barrier across the river, seawater intrusion, and climate changes, etc. where the software has been utilized. The review will enlighten a clarity of the software applicability on groundwater modelling in the Indian context. Conclusions are also drawn where gaps exist and more research needs in India to be focused.***

Keywords: *Groundwater, Flow and Mass Transport Modelling, Visual Modflow, India*.

1. Introduction

The MODFLOW is a MODular 3-Dimensional Groundwater FLOW model was programmed under the FORTRAN 77 language environment with the finite-difference method to describe the movement of groundwater flow and contaminant transportation [1]. It was developed by McDonald and Harbaugh (1984) of US Geology Survey (USGS) in 1984 and had been updated for three times including MODFLOW-88, MODFLOW-96 and MODFLOW-2000 [2]- [5]. The updated version of MODFLOW-2000 could be compiled by FORTRAN language of Visual Studio program, and the general language of C could be used. It simulates steady and non-steady flow in 3-D for an irregularly shaped flow system in which the aquifer layer could be confined, unconfined, or a combination of confined and unconfined conditions. Flow from external sources such as flow to wells, areal recharge, evapotranspiration, flow to drain, and flow through river could be simulated.

But the Visual MODFLOW is a commercial Graphical User Interface for the MODFLOW. It was presented by the 'Waterloo Hydrogeologic' Company in August 1994. The main difference between MODFLOW and Visual MODFLOW is that MODFLOW uses input data in the form of text files which make it complex and time-consuming. Whereas, Visual MODFLOW uses Excel files, Surfer grids, GIS and AutoCAD data as input files. This makes modelling user-friendly and consumes comparatively lesser execution time. Another advantage of the software is that it interprets the raw text and binary output files of MODFLOW by creating color/contour maps and charts. With this, the model results can be easily analyzed and interpreted better. Nowadays the Visual MODFLOW is available as two types: (1) Visual Modflow Classic and (2) Visual Modflow Flex. Both types are similar in all ways, but the only difference is that the former uses a numerical approach while the latter uses a conceptual approach. The objective of this review study is to assess the work that has been carried out in groundwater modelling using MODLOW and Visual MODLOW softwares, particularly in India since its commencement till now. It will enlighten the reader with the versatility of the software and provoke confidence to carry out more studies in the future in the developing country like India.

2. Methodology of groundwater modelling using Visual Modflow

Groundwater flow model includes under steady and transient states by using the finite difference method with the help of Visual MODFLOW [6]. The selective theoretical background for the groundwater modelling is presented in this section. The three-dimensional movement of groundwater of constant density through porous earth material may be described by the following partial differential equation.

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z})=S_s\frac{\partial h}{\partial t}\pm W \quad (1)$$

where, K_{xx}, K_{yy}, and K_{zz}: are values of hydraulic conductivity along the x, y and z- coordinate axes which are assumed to be parallel to the major axes of hydraulic conductivity.

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h: is piezometric head.
W: is a volumetric flux per unit volume and represents sources and/ or sinks of water.
S_s: is the specific storage of the porous material, and
t: is time.

Equation (1) describes groundwater 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.

On the other hand, the partial differential equation describing the 2-D transport of pollutants in groundwater can be written as [7].

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}\left(D_{xx}\frac{\partial C}{\partial x}+D_{xy}\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial y}\left(D_{yy}\frac{\partial C}{\partial y}+D_{yx}\frac{\partial C}{\partial x}\right)-\frac{\partial}{\partial x}(v_xC)-\frac{\partial}{\partial y}(v_yC)+\frac{q_s}{\theta}C_s \qquad (2)$$

where, C: is the concentration of solute dissolved in groundwater at any point; D_{xx} and D_{yy}: are the coefficients of hydrodynamic dispersion along x & y directions, respectively; D_{xy}, D_{yx}: are the dispersion coefficients in the direction 45^0 from x or y-axis; v_x & v_y: are the groundwater velocity in x & y directions, receptively, in the flow domain; q_s: is the volumetric flux of water per unit volume of the aquifer representing sources; C_s: is the concentration of the sources; and θ: is the effective porosity of the aquifer.

Equations (1) and (2) are solved using a finite difference approximation technique. The starting point for the application of this method is the discretization of small rectangular/square sub-regions in a grid form. This leads to set of simultaneous algebraic equations, which is solved using the MODFLOW or Visual MODFLOW modelling code. This code has been widely used and is accepted to produce numerically stable solutions.

It is necessary to understand the steps common to all users involved in groundwater modelling, right from the beginning stages to the final model result interpretations. The simplified steps involved in groundwater model development using software are shown in Figure 1.

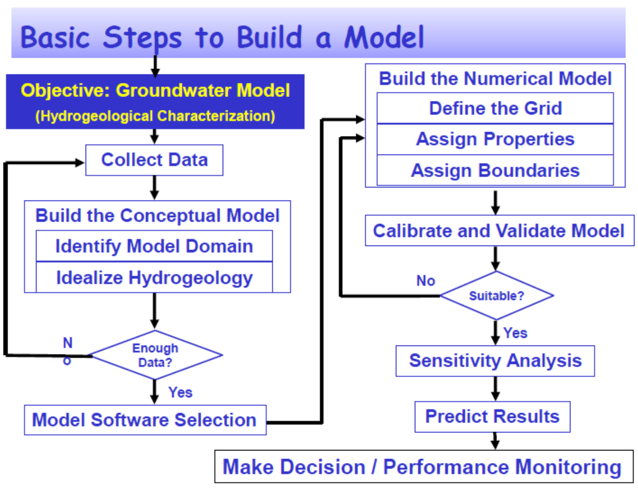

Figure 1: Flowchart for groundwater modelling process using the Visual Modflow [8]

3. A Review Study in India

A general review study on Modflow applications in groundwater modelling was carried by Hariharam and Uma

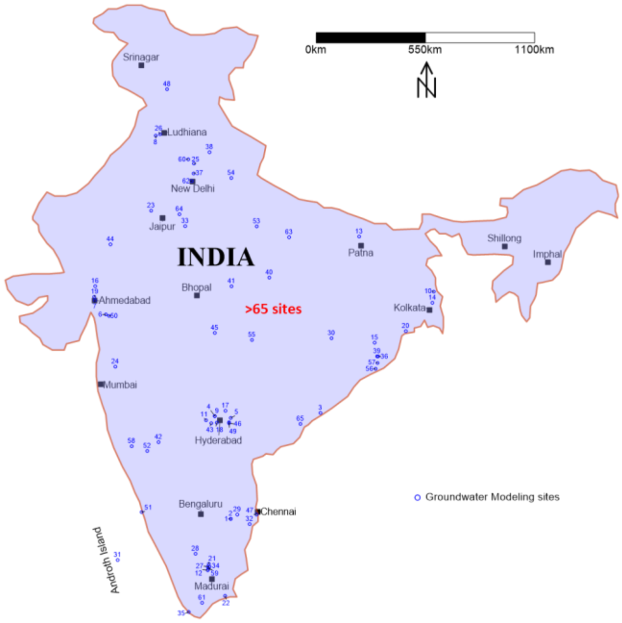

Figure 2: Showing the experimental sites where groundwater modelling works carried in India

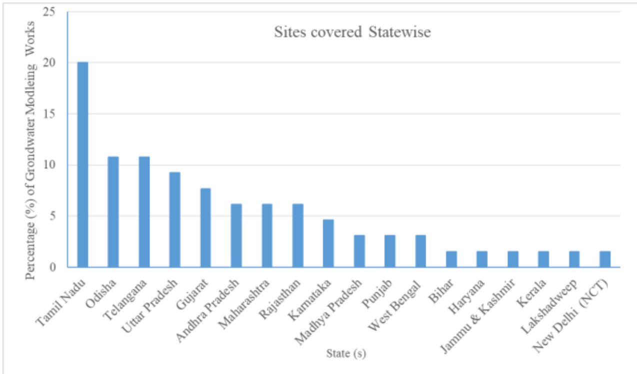

Figure 3: Percentage (%) of groundwater modelling works using Modflow covered in the states of India

Shankar [9]. Out of their 50 citations, they have only listed 16 works from India. Another a review study was also carried by Pathak et al. [10], which consists of only three references from India. They don't provide a wide spectrum of the uses of Modflow for groundwater modelling in India. The groundwater modelling was carried out more than 65 sites till the end of December 2018 on the several aspects in India (Figure 2). More the 50% works were made in the states of Tamil Nadu, Odisha, Telangana and Uttar Pradesh (Figure 3). The maximum groundwater modelling was adopted in the state of Tamil Nadu in India. There was no works related to groundwater modeling using Visual Modflow in the North-East India.

A detail is discussed year wise chronologically order here. First time in India, Gupta et al. [11] conceptualized aquifer in the Upper Palar basin, Tamil Nadu, South India, which had been highly polluted in several pockets due to the discharge of untreated effluents from a large number of tanneries and

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arrived at formed the basis of numerical groundwater flow model. It was constructed using finite difference method using Visual Modflow. The model was calibrated for steady state and then dynamic conditions for the period 1984-92. Mass transport modelling was made using the Method of Characteristics (MOC). Prognosis indicated that the area where in TDS concentration of groundwater more than 4000 mg/l, was likely to be doubled within the next two decades.

In addition, if the tannery effluents continue to be discharged at the level of the year 1999 in the same Palar basin, both as regards the volume and TDS concentration, groundwater pollution would be continued to increase [12]. It was estimated that even if tannery effluents were reduced to about 25% of the year 1999, even after 20 years, the TDS concentration in groundwater would not be reduced to 50% of the original level of the year 1992. A single layer groundwater flow model of the aquifer was simulated in the north-western part of Visakhapatnam urban area using MODFLOW and FLOWPATH computer codes [13]. This urban area was highly polluted as early as 1981 by the discharge of untreated industrial effluent from a Hindustan Polymers Limited (HPL) plant. A total dissolved solids (TDS) concentration of surficial effluent up to 6, 500 mg/l and of groundwater in the range 3000-4200 mg/l had been reported in the environs of the HPL plant during May 1992. The pathlines of particles in groundwater indicated a predominant north-east and south-west migration of groundwater pollution in the area. Since 1978, in Patancheru Industrial Development Area (PIDA) of Medak district, Andhra Pradesh, a number of some chemical and pharmaceutical industries had opened in 1978. Both treated and untreated effluents from these industries were discharged to Nakkavagu and Peddavagu streams, and the former also received effluents from an adjacent Industrial Development area. Groundwater flow and mass transport models were prepared and allowed the extent of contaminant migration from Nakkavagu and other streams to be assessed for the last 20 years [14]. The stream-aquifer interaction was also found to be responsible for faster migration of contamination in the over exploited area around Nakkavagu in Arutla village. Dr. Thangarajan was carried out a preliminary numerical simulation of groundwater flow regime of the phreatic aquifer in weathered hard rock area from Bukderu River basin in Nalgonda district, Telangana [15]. The model study indicated that the phreatic aquifer could be sustained with the withdrawal of 28 x 10^6 rn^3/year without a further decline of water level. Any additional increase of withdrawal in the shallow aquifer resulted in progressive decline of water level, as the average annual dynamic reserve was only about 28 x 10^6 m^3.

Rao and Dhar modelled for assessment and management of groundwater contamination around Gujarat Refinery, Vadodara, Gujarat [16]. Their findings showed that the groundwater contamination was limited to a small area as the wastewater treatment facilities and the associated lagoons were located on low permeability formations in the refinery area. Contaminant transport modelling was performed with MODFLOW and MT3-D models to investigate the increase in the mean nitrate concentration of shallow groundwater in Ludhiana district, Punjab [17]. The concentration was found to be directly related to the increased use of nitrogenous fertilizers. It was revealed that the nitrate nitrogen concentration was above WHO's recommended a limit for drinking water in 68% of the area in the pre-monsoon and in 84% of the area in the post-monsoon periods. The increase in the nitrate nitrogen concentration in groundwater was found to be more in the south-eastern blocks of the district compared to western blocks due to higher usage of nitrogenous fertilizers in the former. Contaminant transport model was observed to be most stable with upstream finite difference numerical method. A combined groundwater flow, pathlines and a mass transport model was also constructed covering an area of 9 km^2 to analyze the capture zone of the French well under two different scenarios [18]. It was found that the predicted capture zone of French well under controlled release of surface water from the Dharoi reservoir was small compared to capture zone under dry river bed conditions. The capture zone of French well under dry river bed conditions had a radius of about 300 m. There were no preferred flow pathways in the river bed aquifer for contaminant migration from three sewage sources. The required travel time for contaminants to reach the capture zone of collector well from pollutant sources was more than a year.

Rao et al. had made groundwater flow and mass transport models at Patancheru Industrial Development Area in Medak district, Telangana where the treated and untreated effluents from the industries were being polluted into two streams (i.e., Nakkavagu and Peddavagu) [19]. The extent of migration of contaminants from the Nakkavagu and other streams had been assessed for 20 years (period:1977-1997). The stream-aquifer interaction was found to be responsible for faster migration of contaminants in the over-exploited area located in the east of Nakkavagu.

An analysis of groundwater flow and transport processes of arsenic in the flow domain of Yamuna sub-basin located in West Bengal was presented [20]. The simulated results of the calibrated model had been replicated the observed monthly water table conditions perfectly. Contaminant transport analysis indicated an in-situ arsenic source. Using the particle tracking algorithm, MODPATH, the possibility of arsenic removal from a sample key location, and the design of wells for withdrawing arsenic-free groundwater were studied through analysis of the well capture zones.

A groundwater flow model was prepared in North-East Musi Basin by assuming 8 to 10% of yearly recharge [21]. From the water balance computation in the steady state, the recharge was estimated as 2.4 MCM. Out of which, about 1.1 MCM was contributed by only lakes. Outflow and draft were also estimated as 0.4 MCM and 2.1 MCM, respectively.

Mondal and Singh had constructed a mass transport model to study pollutant migration at a tannery belt, Dindigul, Tamil Nadu, which was highly polluted due to the discharge of untreated effluents from 80 functional tanneries [22]. This study indicated that transmissivity played a more sensitive role than dispersivity, indicating that the migration phenomenon was mainly through advection rather than dispersion. The study also showed that even if the pollutant

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sources were reduced to 50% of the year 2001, TDS concentration level in the groundwater, even after 20 years, would not be reduced below 50% of the year 2001. Surface and subsurface water logging conditions in Habibpur sub-distributary bounded by Vaishali branch canal and Gandak river in North Bihar for the year 1991-1992 were delineated using groundwater flow modelling software MODFLOW coupling with the integration of Remote Sensing and GIS techniques [23]. Groundwater model revealed that the pre-monsoon (i.e., at the end of June 1991) waterlogged area was about 104.8 km^2 while the post-monsoon (i.e., at the end of October 1991) waterlogged area was about 128.2 km^2. The study clearly demonstrated the utility of integration of remote sensing and GIS techniques with groundwater flow modelling for assessment of waterlogged areas particularly in regions where waterlogging conditions occurred both due to excessive irrigation and accumulation of rain and flood waters. Locating arsenic-safe water tube-wells using MODFLOW software could be given a long-term remedy in Yamuna sub-basin which was initially giving potable water in-term of Arsenic. Hydrostratigraphy of the study domain was conceptualized up to a depth of 140 m considering three principal sediment groups (i.e., Clay, Sand, and Sand and Gravel). This study indicated that the arsenic concentration in sediment and groundwater does not reveal depth-wise trend. But Deviation Factor (DF) indicated irregular trend of concentration levels in sediment as well groundwater depth-wise [24]. Statements on acquisition of arsenic free groundwater were site-specific. These necessitate modelling based decision making for safe well location. Secondly, all the DF values are negative, which means that arsenic in sediments is depleted concerning their world average values. To locate safe drinking water wells in the Yamuna sub-basin, the modeler should incorporate depth specified hydro-stratigraphy and field constraints. The hexavalent chromium (Cr^{6+}) migration was simulated from chromite deposits of the Sukinda valley in Odisha [25]. The path lines of Cr^{6+} migration were simulated for 20 years in 2-layered model of groundwater. It provided an insight into the likely migration of contaminant in groundwater due to leaching from overburden dump of chromite ore. In addition, the role of mathematical modelling in groundwater resources using Modflow particularly in mining areas in India was discussed in the details [26]- [27].

A Geographical Information System (GIS) assisted approach that couples a groundwater flow model and an inverse geochemical model was presented to quantify the phase mole transfers between two points on the flow path within a groundwater system. It was used to investigate the plausible phase transfers in the unconfined aquifer of Mehsana district of Gujarat State, India [28]. The groundwater flow field was simulated using MODFLOW, and flow paths used for inverse geochemical modelling were traced using PMPATH, a particle tracking algorithm. A groundwater flow model of Upper Musi basin using MODFLOW was prepared [29]. The groundwater extraction had been estimated about 177.5 MCM and river leakage was estimated as 120 MCM and outflow being 0.4 MCM. It assumed the recharge of 8-l0% from the total annual rainfall according to model for the entire Musi Basin. Mean annual simulated recharge was 1176 MCM (17% of total rainfall) while annual pumping was estimated at 1235 MCM. Simulated base flow was 23 MCM while river leakage was less than 1 MCM. Among the total simulated annual recharge, groundwater irrigation return flow to the aquifer was estimated at 370 MCM and artificial recharge at 124 MCM. Natural recharge from rainfall was accounted for 652 MCM. The sustainable groundwater withdrawal yield over the period was around 1,220 MCM for the total basin.

In order to assess aquifer renewable reserves and help groundwater management authorities, a fully distributed physical model of the aquifer from Musi River sub-basin (area: ~11,000 km^2), which was one of the main tributaries of the Krishna River, located in Andhra Pradesh, had been calibrated and validated for a transient state experienced during 1989-2004 by using MODFLOW [30]. The key variables such as aquifer storativity and transmissivity were determined by inverse fitting of simulated and observed groundwater levels.

A research paper coupling of one filtration theory to MODFLOW was introduced [31]. Simulation of clogging effects during “Hansol” well recharge in Ahmedabad of Western India was found to be encouraging. A 2-D groundwater flow of an overexploitation of groundwater area from Balasore coastal basin, Odisha district was simulated [32]. The analysis of the aquifer response to various pumping strategies indicated that the Balasore aquifer system was more vulnerable to the river seepage, natural recharge and interflow than the horizontal and vertical hydraulic conductivities and specific storage. The most promising management strategy for the Balasore basin could be a reduction in the pumpage from the second aquifer by 50% in the downstream region and an increase in the pumpage to 150% from the first and second aquifer at potential locations.

A pollutant transport model for the migration of tannery effluent contaminants around a tannery industrial belt in Southern India was developed [33]. It was reported that the migration phenomenon was affected mainly by advection rather than dispersion. The contaminant transport originated from the tannery belt and moved towards eastern side of Kodaganar river downstream. The knowledge of aquifer characteristics, ascertaining groundwater movement and its flow direction in the east coastal belt, Tuticorin of the state of Tamil Nadu encompassing an industrial complex using Visual Modflow had been gained, which would, in turn, reveal the possibility of contamination of groundwater regime and its better management [34]. The model indicated that the velocity of groundwater flow varied from 0.013 to 0.22 m/d in and around the industrial complex in upstream western part of the catchment and 0.026 to 0.054 m/d in the downstream eastern part near the coast. The groundwater flow model was developed and calibrated the northern part of Mendha sub-basin in the semi-arid region of north-eastern Rajasthan against the historical and observed water level data for the period of 1998 to 2003 and 2003 to 2005, respectively [35]. In this study historical data of water level was divided into two parts, in the first part of data from year 1998 to 2003 were used for the calibration purpose. In the second part the available field data during year 2003 to 2005 were used for model verification. Then the model was run to

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generate groundwater scenario for a 15-year period from 2006 to 2020 considering the existing rate of groundwater draft and recharge. The water budget predictions indicated a decrease from 349.50 to 222.90 MCM in the groundwater storage system, whereas groundwater abstraction showed an increase from 258.69 to 358.74 MCM per annum. The 3-D groundwater flow algorithm MODFLOW had been used to develop the base case model in a mountainous watershed from the Maharashtra state of India, incorporating observed subsurface flow conditions [36]. It was indicated that the interflow followed an integrated and continuous hydraulic gradient across multi-aquifers. Finite aquifer extents also supplement the recharge and discharge processes. Another groundwater flow modelling was carried out at a part of Yamuna–Krishni interfluve in Uttar Pradesh in Visual MODFLOW, Pro 4.1[37]. The zone budget showed a water balance deficit for the period June 2006 to June 2007. The total recharge to the study area was 160.21 MCM. The groundwater draft through pumping was of the order of 233.56 MCM, thus leaving a deficit balance of −73.35 MCM.

Kumar et al. developed a groundwater model using Visual MODFLOW software to understand the reasons for declining water table in Central Punjab, India [38]. The groundwater flow model for the study area was formulated by using input hydrogeological data and appropriate boundary conditions. The outcome of modelling showed that this model could be used for prediction purpose in the future by updating input boundary conditions and hydrologic stresses during the preceding years. Rajamanickam and Nagan modelled the groundwater using Visual MODFLOW 2.8.1 version around Amaravathi river basin of Karur District, Tamil Nadu to assess the effect of discharging partially treated effluents from textile bleaching and dyeing units [39]. Total Dissolved Solids (TDS) migration was simulated for 15 years under five different scenarios. The calibrated results showed that there was no improvement in groundwater quality even the effluent met the discharge standards for the next 10 years. When the units used for zero discharge then there could be an improvement in the quality of groundwater over a period of few years.

Transient mode groundwater flow model simulated using visual MODFLOW version 4.1 for the year 1998–99 at textile effluent affected areas in Tirupur basin, Tamil Nadu and demarcated the groundwater protection zones [40]. The modelled zones were ranked and their need for keeping them pollution-free was stressed for the better aquifer management. Groundwater contamination had been assessed around a dumpsite near TCCL at Ranipet, India where the chromium levels in the groundwater were found up to 275 mg/l [41]. Migration of chromium plumes in the groundwater were simulated for 30 years. The migration had been found to be very slow, with a groundwater velocity of 10 m/year. The findings were of relevance to addressing the groundwater pollution due to indiscriminate disposal practices of hazardous waste in areas located on the phreatic aquifer. Rice-dominated cropping system in Hirakud Canal Command, Orissa of Eastern India was under severe threat due to imbalance between irrigation water supply and demand. The canal water supply, which was the only source of irrigation, only met 54% of the demand. Therefore, Raul et al. was carried out a quasi-3-D groundwater flow simulation modelling by using Visual MODFLOW to detect the change in hydraulic head due to transient pumping stresses [42]. The results showed that groundwater extraction could be increased up to 50 times of the existing pumping without causing any adverse effect to the aquifer but the aquifer did not allow to exploit water in order to fulfill the irrigation water demand. The density driven groundwater flow was simulated using SEAWAT (MODFLOW and MT3-D based computer program) model in Androth Island Lakshadweep, India [43]. The model was utilized to derive optimal pumping rate and the effect of artificial recharge. It had proved that the salt-water intrusion could be stopped by raising the water level through temporarily storing the artificially recharged water post construction of subsurface dam near the coast. In order to meet the increasing demand for groundwater for the nuclear power station, a subsurface barrier/dam was proposed across Palar River, Tamil Nadu to enhance the groundwater heads and to reduce the subsurface discharge of groundwater into the sea. Senthilkumar and Elango had prepared a groundwater flow model to assess the effect of a planned subsurface barrier on groundwater flow in this area [44]. The groundwater model used in this study predicted that groundwater levels would increase by about 0.1–0.3 m extending out a distance of about 1.5– 2.0 km from the upstream side of the barrier, while on the downstream side, the groundwater head would lower by about 0.1–0.2 m. The model also predicted that with the subsurface barrier in place the additional groundwater requirement of approximately 13,600 m^3/day could be met with a minimum decline in the regional groundwater heads. A methodology for groundwater evaluation by the combined use of numerical model using MODFLOW and spatial modelling using GIS had developed and applied on a sub-basin of the Banganga River, Rajasthan [45]. Developed groundwater flow vector map had been superimposed on the potential zone map to validate the results of spatial modelling. Finally, the different scenarios had been conceptualized by varying the discharge of the wells and purposing the location for new rainwater harvesting structures. Results revealed that increasing the discharge of the wells in the potential zones put less stress on the aquifer. The suggested locations of rainwater harvesting structures also helped to reduce the overall decline of groundwater level.

Chloride migration was simulated in a tannery belt of Dindigul, Tamil Nadu, Southern India using Visual MODFLOW Premium 4.4 software [46]. Results showed that hydraulic conductivity played a more sensitive role than did dispersivity for Cl_2^-migration. This migration was mainly through advection rather than dispersion. It was found that even if the pollutant load reduced to 50% of the year 2009, the Cl_2-concentration in groundwater, even after 6 years (in Year 2015), would not be reduced to the permissible limit of drinking water. A coastal aquifer of Trivandrum, Tamil Nadu was simulated for groundwater flow and contaminant migration using Visual MODFLOW [47]. Groundwater heads in the observation wells near the pumping wells were predicted for ten years (2011-2020) using the observed water levels at the observation wells for a period of one year. A contaminant transport model was also developed using

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SEAWAT and the effect of 1% increase in pumping on intrusion was studied. Predicted groundwater heads in most of the observation wells showed a decreasing trend. This decreasing trend in groundwater heads created a landward hydraulic gradient which led to seawater intrusion into the coastal aquifers of Trivandrum. The lateral extent of seawater intrusion was more at Karikkakom pumping well location when compared to all other well locations due to 1% increase in the pumping.

A transient simulation-optimization model was prepared for a study area of Kathajodi–Surua inter-basin, located in Orissa state in Eastern India using Visual MODFLOW [48] and also used the response-matrix technique to maximize pumping from the existing tube wells for determining optimal cropping patterns in the wet, normal and dry scenarios. The results of simulation-optimization modelling indicated that if the suggested optimal cropping patterns were adopted in the study area, the net annual irrigation water requirements would be reduced by 28, 35 and 40%, and net annual income would be increased by 28, 23 and 17% during wet, normal and dry scenarios, respectively. Groundwater flow modelling of multiple aquifer systems in Hindon-Yamuna interfluve region was simulated using Visual MODFLOW Pro 4.1 for the behavior of the flow system and evaluating the zone budget [49]. Results indicated that the total annual direct recharge was 416.10 MCM and the total annual groundwater draft through pumping was of the order of 416.63 MCM. Inflows from Hindon and Yamuna rivers were 24.2 and 30.0 MCM, and the estimated base flows were 0.43 and 1.7 MCM, respectively. The scenarios were also generated to predict the drawdown during the period from 2008 to 2018. It was observed that north-eastern, north-western and south-eastern parts of Hindon-Yamuna interfluve region were drastically affected with maximum drawdown of >6.0 m for the recharge constant and withdrawal rate increased by 20% for 10 years (2008-2018). A framework for an integrated hydrological, hydrochemical, and groundwater quality model using SWAT–MODFLOW–MT3-D MS was carried out in a Himalayan watershed (namely the Upper Yamuna watershed, a part of Ganga river basin) to obtain groundwater flow and NO3 transport [50]. Results on surface runoff and groundwater levels obtained as outputs from simulation showed a good comparison with the observed stream flows and groundwater levels. Nitrate modelling in groundwater aquifers were compared with observed NO_3-concentration and were found to be in good agreement. A groundwater flow model for Kathajodi–Surua Inter-basin of Odisha had also developed using finite difference-based Visual MODFLOW software for simulating groundwater levels [51] and coupled with artificial neural network (ANN) models for forecasting groundwater levels. The results concluded that the numerical models like MODFLOW provided the total water balance of the system, whereas the ANN models were like a ‘black box’ and they did not describe the entire physics of the aquifer system. The numerical models were more appropriate for long-term predictions, whereas the ANN technique was better for short-term predictions that require a high accuracy. Surinaidu et al. developed a model using USGS flow code (MODFLOW 2000) for a limestone mining activity area in Katni, Madhya Pradesh in which it had become necessary to increase the depth of exploration to produce ore [52]. The steady flow model was calibrated under the pre-development conditions assuming an equivalent porous medium approach. Water budget showed that the total groundwater flows into the aquifer system due to interaction with river amounts to 14,783 m^3/day. The inflows into the mine pits were estimated as 15,725 m^3/day. This could be utilized to predict the required amounts of pumping and the possible locations to dewater the groundwater in the mining pits. Kant et al. modelled the groundwater system situated in the alluvial plains in Sonar sub-basin in Madhya Pradesh [53]. The model was found to agree with the observed records and indicated reasonable declination of groundwater levels during the study period. A 3-D steady-state finite difference groundwater flow model was made for alluvial aquifer of the Ghatprabha River of the Karnataka to quantify the groundwater fluxes and analyze the subsurface hydrodynamics [54]. The results indicated that the groundwater flowed regionally towards the south of the catchment area and the migration of contamination would be reached in the nearby well field in less than 10 years.

Another groundwater flow model for Osmansagar and Himayathsagar catchments was developed under transient conditions using Visual MODFLOW software for the period 2005 to 2009. The model indicated that the average input to the aquifer system was 321.96 MCM, and the output was 322.14 MCM [55]. If the same withdrawal was continued up until the year 2020, the water level was believed to decline >45 m over the entire study area. To avoid this critical stage, the draft should be decreased by nearly 40%. In Pali area of Rajasthan state groundwater flow model had been developed using MODFLOW-2000 to predict groundwater flow regime and to model the variability of rainfall and subsequent variations in groundwater recharge to capture its impact on groundwater regime [56]. It concluded that the variations in the water table were more prominent in the eastern part of the study area. However, the area around river Bandi remained unaffected, indicating that variation in rainfall does not had a significant impact on the post-monsoon groundwater regime in this area. Another groundwater flow model had been developed at Warud taluka of Amravati district, Maharashtra to evaluate the groundwater system [57]. The modelling results showed that the unconfined aquifers in Bazada were drying up (water level: >15 m bgl) of 243 km^2 area by the year 2020. To restore the groundwater level, it was simulated that the groundwater draft rate must be reduced by 20% for the next 10 years. Kumar and Kumar developed a groundwater flow model to quantify groundwater in Choutuppal Mandal, Telangana [58]. The water budget estimate was also made. The model showed that groundwater entered from Borrollagudem and leaved at Aregudem and Katrevu through Choutuppal area.

Parameswari and Mudgal analyzed the leachate migration from a dump yard at Perungudi, Chennai, India [59]. The groundwater flow model was calibrated for transient conditions and chloride migration was also simulated for 12 years (2008-2020). The modelling results revealed that the contaminant might migrate for a distance of 4.5 km within 12 year upto 2020 under the prevailing condition along the south eastern direction. If the dumping increased by twice, the contaminant concentration would get doubled in a period 10

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years and if the recharge increased by 10%, the contaminant concentration got diluted from 600 to 100 mg/l which might be due to recharge from the marsh which favoured higher dilution. Groundwater seepage issues were studied by applied Visual MODFLOW in subsurface tunnels between Katara and Udhampur in Jammu and Kashmir [60]. It was created a 3-D finite difference model with the help of inferences made from hydro-geo-morphological features and geological lineaments to investigate the groundwater seepages. The computed flow model indicated that Tunnel would receive groundwater seepage of 78,133 m^3/day. The analysis of the model results revealed that 500 lateral perforated pipes of 5 m in length at an interval of 2 m with an annular space filled with highly permeable geo-media could drain out the seepage water. The suggested perforated pipes were successfully installed in the Tunnels. They were effective in draining out the groundwater seepage. By using Visual MODFLOW 4.2 premium software, the shallow weathered and fractured zones in a watershed situated near Choutuppal village, Telangana was simulated in steady state [61]. It was observed that groundwater flow was towards the north side of the area. Groundwater velocity was 0.038 m/d in x-direction, 0.259 m/d in y-direction and 0.00022 m/d in z-direction. An overdraft was observed about 2.761 m^3/d due to excess of draw out of water for various requirements. Contaminant transport modelling was carried out in Vadodara Metropolitan City, Gujarat [62] and revealed advancement of containment plume as a result of increasing level of pesticide in river Vishwamitri. The restoration of the aquifer system might take a very long time as seen from slow improvement in the groundwater quality from the predicted scenarios for different years, thereby indicating an alarming situation of groundwater quality deterioration in different layers. It was recommended that all the industries operating in the region should install efficient effluent treatment plants to abate the pollution problems. A variable density numerical model, SEAWAT-2000 (a coupled version of MODFLOW and MT3-D MS) was used to conceptually simulate groundwater flow and transport for a coastal stretch located the rivers Shambhavi and Pavanje in Karnataka, India [63]. The flow simulation results showed that the hydraulic head contour was a rising trend from the coastline (0 m). The transport simulation showed that the TDS-isoline of 2kg/m^3 encroached the area by 200 to 400m more landward in certain areas near the coastline during the dry season. This was also indicated by the water budget outcome, which showed a total inflow and outflow across the constant head boundary (sea) of 664.40 m^3/day and zero, respectively, during the dry period(May). Another two layered conceptual model of aquifers within Ramdurg, Saundatti (Belgaum district) and Nargund taluks (Gadag district) in Karnataka was prepared using Visual MODFLOW Flex version 2014.2 [64]. Results indicated that the groundwater flow was taking place in two different directions in the study area and was in accordance with the topographical elevation. The continuous increase in the groundwater head was observed in second layer as the years progressed. Surface water from the Reservoir was contributing to the groundwater in the southern portion of the study area while it remained unaffected to the northern portion of the study area, respectively.

A three-dimensional groundwater flow model of Ganga basin was developed [65]. The results showed with the over exploitation of the groundwater, most of the river stretches had become either loosing or were gaining much lesser amount of water from the groundwater. The hydraulic conductivities of the river bed and the aquifer were more spatially refined. Two-layer system of Ramganga sub-basin from Ganga basin was simulated using MODFLOW and SWAT [66], in a semi-coupled modelling framework from 1999 to 2005 and validated from 2006 to 2010. The results showed that the pumping of 0.25 Bm^3/year before monsoon creates 3–4 m subsurface storage (SSS) by 2020. Base flows were predicted to fall by 30% with increased pumping by 2020. Controlled pumping and recharge enhance storage by 14% and river seepage 31%. Increased rainfall scenario would enhance recharge by 44% and base flow by 11%. A steady state groundwater flow model of Basalt formation located at Nagpur Urban area, Maharashtra was calibrated to evaluate the subsurface system using Processing MODFLOW (PMWIN 5.3.2). The calibrated hydraulic head was compared with the field observed head [67]. The comparative spatial analysis presented a simple integrated approach in identifying zones with falling groundwater trends suitable for groundwater recharge in hard rock terrain in Nagpur urban area. Ritesh Vijay and Mohapatra used modelling to assess the safe yield of groundwater withdrawal and quantified the future demand of water supply for the city of Puri, Odisha, which was being subjected to constant sea water intrusion and continuous freshwater withdrawal due to the pumping [68]. Results showed that the fresh groundwater flowed toward the sea during monsoon and post-monsoon, production wells near the seaside should be utilized more for withdrawal and supply as compared with the inland production wells. The model was also suggested that any additional production well should be installed and practiced in the middle of the water fields to minimize adverse impacts on the groundwater resources.

A quasi-3-D transient groundwater flow model was designed using MODFLOW to simulate the groundwater system of Mahanadi River Delta, Odisha, Eastern India [69]. The model was constructed in the context of an upper unconfined aquifer and lower confined aquifer, separated by an aquitard. Hydraulic heads were used to calibrate transient groundwater conditions during 1997–2006, followed by validation (2007–2011). The simulation results indicated that pumping had a substantial effect on the confined aquifer flow regime as compared to the unconfined aquifer. The results and insights from this study had important implications for other regional groundwater modelling studies, especially in multi-layered aquifer systems. A 3-D groundwater flow model, viz. Visual MODFLOW was used for the study with two conceptual layers of Hiranyakeshi watershed of Ghataprabha sub-basin, Maharashtra [70]. The first layer was a weathered zone which was about 20-30 m from the top, followed by a second layer of the fractured zone which was about 30-40m from the first. The model was simulated for a period of 7 years (2008-2014), under transient mode. The results from the modelling showed that for the next 10 years the water table was believed to decrease more than 50 m in the study area. To overcome this critical stage, the draft should be reduced by

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nearly 50%. A watershed located in Kodaganar river basin, Dindigul district, Tamil Nadu was simulated using MODFLOW software coupling with the Geographic Information System (GIS) for identification the suitable sites for artificial recharge structures to augment groundwater resources [71]. Three-layer groundwater flow model was developed and calibrated in two stages, which involved steady and transient state conditions. The transient calibration was carried out for the period from January 1989 to December 2008. The groundwater model was validated after model calibration. The prediction scenario was carried out after the transient calibration for the period of the year up to 2013. The results showed that there was about 15 to 38% increase in groundwater quantity due to artificial recharge which was recommended based on the results of GIS.

HYDRUS 1-D and MODFLOW models were used to simulate the climate change impacts on groundwater recharge for different projected climate change scenarios in Karnal district of Haryana state in India [72]. Simulation results showed that groundwater recharge would increase marginally by 2030 over the baseline year of 2008 under the scenario based on ARIMA predictions, which considered the effect of all climate parameters. However, under the scenarios, which considered the rise in temperature, groundwater recharge would decrease by 0.07-0.22 m. Rise in temperature by 3.50C and 4.30C along with 9% and 16% increase in rainfall over the base year would increase the recharge by 0.09 m and 0.14 m, respectively. A MODFLOW model was developed to estimate water budget of a part of Tirunelveli Taluk, Tirunelveli District, Tamil Nadu [73] with the known boundary conditions and field observations. The results showed that the water budget of the entire area was negative and equal to 103.679 cubic meters in the year 2011. A variably saturated zone flow model HYDRUS 1-D along with groundwater model MODFLOW was used to simulate vadose zone flow processes, recharge flux and groundwater recharge at the Indian Agricultural Research Institute (IARI) farm, New Delhi [74]. Results suggested that the evapotranspiration was a major recharge control parameter in semi-arid regions. About 61% of the rainfall went as evapotranspiration (ET). A considerable portion of soil moisture stored in vadose zone was lost as ET. Average cumulative recharge flux was 31.28% of the monsoon rainfall. Under prevailing pumping conditions, net groundwater recharge was 23.20% of the monsoon rainfall. Excessive groundwater pumping was the major reason for water table decline. In the absence of groundwater pumping, the average groundwater recharge would have been 30.60% of the monsoon rainfall which was close to an average cumulative flux of 31.28%. A groundwater system model had been developed for Sai–Gomti interfluve region, Uttar Pradesh, India using Visual MODFLOW [75]. The model had been simulated in both steady state and transient state for 8-year stress period. Further, this calibrated and validated model had been utilized to predict the groundwater levels from the year 2014 to 2018 considering the effect of varying pumping and recharge rates. The simulation results showed that the groundwater level was declining in Sai–Gomti interfluve region due to excess withdrawal of groundwater mainly for agricultural activities. A numerical groundwater flow modelling carried out in Baswa-Bandikui watershed in Dausa district of eastern Rajasthan to generate futuristic groundwater management scenarios revealed that even after adopting groundwater development regulation measures, artificial recharge to groundwater and micro-irrigation techniques, the alluvium aquifer in a substantial area would get de-saturated by the year 2024 [76]. Recently, **Prasad and Rao** were constructed groundwater flow model for a micro-watershed of 50 km^2 namely 'Konda Kalava watershed' of 'Suddegedda river basin' located in the non-command upland area of East Godavari district [77]. The water budget analysis had showed that the total groundwater extraction by pumping wells was 83.3% and evapotranspiration loss was 5.7% of the total groundwater recharge in the basin with the maximum groundwater velocity of 0.4 m/day. It was recommended that, for at least one season, the most affected dry areas which were under paddy cultivation were to be promoted irrigated dry crops such as maize and jowar.

4. Conclusions

It is noticeable from this review that the MODFLOW software has found the applicability in a diversity of groundwater flow and pollutant transport simulation. The models have been used in a several parts of India, but it was not so extensive uses and no body tested the post-audit model although showing an optimistic research potential with this commercial and user-friendly MODFLOW package. It is also noticed that the maximum groundwater models are developed in the state of Tamil Nadu in India but there is no model available with help of Visual MODFLOW in the North-East India. In abroad, Middle East and Asian countries (exclusively China) have extensively used this commercial software than other nations. This review indicates that the similar research could be replicated in other countries as well in several parts of India. Dynamic interaction between surface and subsurface water is the prime importance nowadays to understand complete hydrological cycle for the effective management of water resources particularly in India for the Water Security. A couple model with integrating other modelling software such as GIS, GRACE, SWAP, SWAT, etc. with the Visual MODFLOW have been approached in some studies. Such approaches enhance the novel findings to the cutting edge research in future.

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Author Profile

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