Indian Journal of Geo-Marine Sciences
Vol. 45(1), January 2016, pp. 111-116

Application of groundwater modelling for sustainable management: Few case studies from India

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Received 07 July 2014; revised 24 August 2015

Few case studies on groundwater models applied to understand the flow and solute transport in parts of southern India are presented. These examples showcase the ability of mathematical models to aid in decision making processes towards sustainable management of groundwater resources.

[**Keywords:** numerical model; geochemical model; unsaturated zone modelling; Tamil Nadu; Telangana; India]

Introduction

Groundwater is under considerable stress to fulfil the needs of the population which will ultimately lead to deterioration of its quality. Excessive extraction for irrigation is the main cause for aquifer depletion and climate change has the potential to exacerbate the problem in some regions of the world[1]. There is growing concern throughout the world about the contamination of groundwater as a result of anthropogenic activities such as use, spill or disposal of agrochemicals, pesticides, insecticides, petroleum products/by-products, industrial chemicals, their waste products and improper disposal of household wastes. Natural causes of groundwater contamination are mainly due to the lithology i.e. the mineral composition of the rocks inherent to an area. As groundwater is an important and essential component to be preserved for generations to come, several techniques are being used to predict and monitor its quality and quantity over years. In the technologically advancing world, groundwater modelling has been developed as one such tool for proper and effective management of water bearing aquifer formations. Groundwater models are mathematical and digital tools which help to analyse and predict the behaviour of aquifer systems on local as well as regional scale, under varying geological environments, conditions, external factors and help in bringing out the most suitable and sustainable solution[2]. This involves complex factors and also interaction between these factors in the system. Different scenarios can be assumed and groundwater flow and contaminant transport can be modelled to understand the consequences. Proper groundwater flow and solute transport modelling with intensive geological and hydrogeological investigations supported by laboratory studies will help in effective groundwater management. Some applications of groundwater modelling that had helped to manage the resource and in formulating management strategy are compiled here.

Sustainable management of groundwater resources

Groundwater- surface water interaction

Groundwater is used intensively in the Cauvery delta of south India (Fig. 1) for domestic water supply and irrigation because the water demand met from surface water bodies is insufficient. The relation between groundwater chemistry and the local geological and hydrogeological conditions was studied with the help of the finite difference flow model (MODFLOW). Seawater intrusion in the coastal parts of this region along with contamination from the ground surface such as improper disposal of wastes, sewage/drainage canals near the wells, irrigation return flow and application of synthetic fertilizers and farm manures were influencing the groundwater quality[3]. The process of building up of solutes in the eastern part of this area was studied by the simulation of chloride concentration which is likely to be derived by seawater mixing especially in coastal region and nitrate which is derived from agrochemicals[4]. The flow to be maintained in the river and rainfall recharge required to flush the ions into the sea was ascertained and it was concluded that if there is continuous flow in the river, the ions will be flushed into the sea. If the accumulation of ions in this region continues, the soil salinity will increase and it may be necessary to change the cropping to more salt resistant crops. Simulation of solute transport until the year 2020 predicts that groundwater dilution will take place only if the river flows at least for 90 days in a year[4].

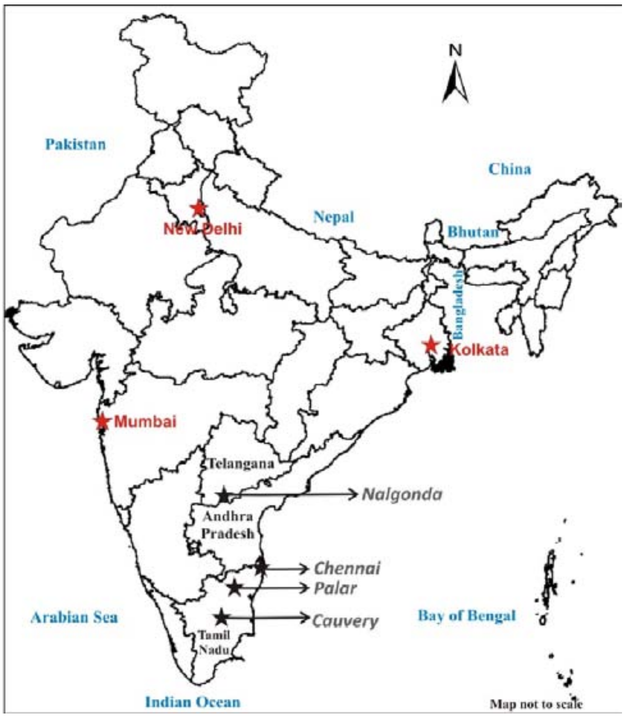

Fig. 1—Location of case studies discussed

Impact of rainwater harvesting structures

A preliminary study was carried out using a numerical model to investigate groundwater conditions for the Chennai City (Fig. 1) where groundwater has been extensively used for domestic purposes. Groundwater occurs in weathered/ fractured rocks and at a few places in unconsolidated sandy formations. It was reported by the Central Ground Water Board that there has been alarming decline in groundwater table in several parts of the city due to over exploitation of resources when rainfall is scanty. In order to overcome this problem the Government has brought in legislation, there by all buildings need to have rainwater harvesting structures. Groundwater modelling study was used to indicate the effect of these measures on the groundwater conditions of this city. This region was hypothetically divided into smaller cells and for each cell the geology, subsurface conditions and hydraulic parameters were assigned. Within this discretised domain, the variable internal properties, boundaries, and stresses of the system were approximated. The model developed for the City was capable of simulating the groundwater table over this area for the given recharge and pumping conditions. The results of simulations performed with normal rainfall recharge and with uniform 10% increase in recharge indicated that the groundwater levels are likely to increase by 2 to 6 m (Fig. 2). This model helped to understand the impact of rainwater harvesting structures on groundwater levels in a major city.

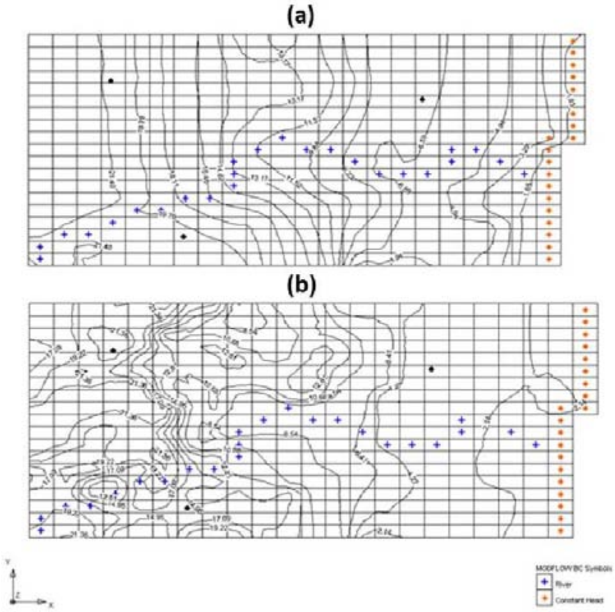

Fig. 2—Simulated groundwater level (masl) in Chennai city (a) with present level of rainfall recharge and (b) with anticipated increase in recharge with rainwater harvesting structures (+ - Adyar River, * - Bay of Bengal)

Highly stressed coastal aquifer

Coastal aquifers especially the one's along major cities are under stress due to groundwater pumping so as to manage the growing needs of the cities and its peri-urban areas. To meet Chennai's requirement about 16,090 m^3/day of water is pumped by private and government agencies from the coastal aquifers located in the southern part of the city. Apart from these there are private bore wells in many households to meet their domestic water needs. This was a complex aquifer bounded by Bay of Bengal in the east, Muttukadu estuary in the south, Adyar River in the north and there is also the Buckingham canal which passes through this area along N-S direction. All these water bodies are saline in nature. With such hydrologic stress the fresh groundwater aquifer in this area was at threat of contamination and seawater intrusion. A model was developed using Groundwater Modelling System (GMS) to understand the behaviour of the aquifer with the changes in hydrological stresses[5]. The effect of increase in pumping and the changes in the rainfall pattern simulated from the model predicted that the aquifer can be sustainably managed with the pumping rate of 16,090 m^3/day, but, if the pumping was increased there will be seawater intrusion and subsequent salinization of the aquifer. Sensitive areas along the coast which showed negative effects on the aquifer even for 5% reduction in recharge was also identified[6]. The model developed was useful as a management tool for this aquifer system.

Assessing feasibly for pumping of seawater for a desalination plant

Feasibility of having a beach well for pumping the required quantity of seawater for the proposed desalination project in Nemmili village located along the coast of Bay of Bengal near Chennai city was assessed using groundwater modelling (GMS v.6)[7]. This study required intense understanding of the subsurface characteristics of the area which was brought out from field visits, electrical resistivity survey, drilling of new boreholes and pumping tests. It was essential to rightly decide on the quantity of seawater to be pumped failing which might result in negative impact on the fresh water aquifers occurring near the coastal region. Model predicted that the beach well which will be constructed to draw water at the rate of 10,000 m^3/hr for 365 days will not be able to possibly extract water as the wells went dry. Simulated chloride concentration in groundwater after 365 days while pumping a beach well at the rate of 7000 m^3/d is shown in Fig. 3. Pumping at this rate also leads to increase in chloride concentration over the entire area. Even going for four beach wells each with a pumping rate of 2,500 m^3/hr for 365 days was not possible as this will reduce the groundwater level on the west where the people are dependent on private wells. It was not advisable to pump the required large quantity of water for the desalination plant from this site which in due course might turn the fresh groundwater of this region saline[7].

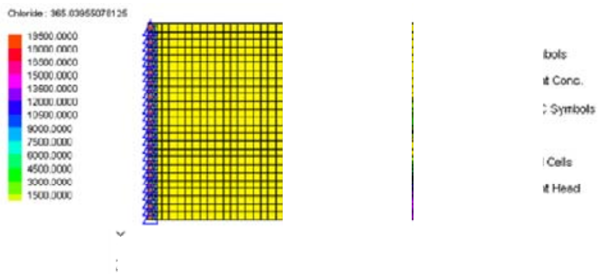

Fig. 3—Simulated chloride concentration in groundwater after 365 days while pumping a beach well at the rate of 7000 m^3/d

Impact of 2004 tsunami and relocation of wells

Numerical models can be used to predict the impact of natural disasters such as flooding, tsunami, etc. A model was constructed to study the deterioration in groundwater quality in the coastal parts of Chennai city due to the massive tsunami that occurred on 26th December 2004, triggered by a 9.2 magnitude earthquake off the west coast of Sumatra. The Tsunami had induced salinity in the groundwater of this area. The model developed using FEFLOW to understand the process of salinisation by groundwater flow and solute transport for a period of two years from 2005 to 2007 showed that the salinity would reduce by natural attenuation due to annual rainfall recharge. It was brought out from the model that cleaning up of the salinized aquifer will be possible without human interference by natural rainfall recharge within a period of 4 years[8]. Hence, no expensive means of groundwater treatment was necessary as natural recharge will remediate the aquifer system. Relocation of wells in some of this area was required and these wells were identified from the model. This was tested by post auditing through collection of groundwater samples and chemical analysis which complied with the results of the model. The water quality improved in 2008 and had reached the pre-tsunami levels than the groundwater concentration of various ions recorded immediately after tsunami. This kind of application of numerical models to environmental scenario will help in taking suitable management measures at the appropriate time.

Impact of sub-surface barriers

The Palar River is a seasonal river and flows only for few days in a year. Hence, groundwater is used more widely for various needs in this area. A groundwater model was developed using GMS for the Palar River basin (Fig. 1) of south India to manage the aquifer system to different hydrological stresses induced naturally and by external sources[9]. This study concluded that the level of abstraction from the aquifer for domestic as well as industrial needs mainly by the Madras Atomic Power Station (MAPS) was found sustainable. Apart from this, several future scenarios were considered like increased pumping for the MAPS, predicting dry years once in 4 years based on long term rainfall data as well as the management needs to protect the groundwater levels. It was anticipated that with an expansion of MAPS, pumping will be increased by an additional ~9,000 m^3/day to 13,600 m^3/day i.e., 2 million (UK) gallons per day (MGD) to 3 MGD. With an increased pumping of ~9,000 m^3/day, the groundwater level declined on the eastern part of the area i.e. towards the coast even below the sea level with increased risk of seawater intrusion. Even under normal rate of pumping the groundwater head is lowered below the sea level during the dry seasons. To overcome this, it was proposed to construct a subsurface barrier across the Palar River to increase the groundwater heads, to minimise the subsurface discharge of groundwater into the sea and to prevent seawater intrusion in the coastal parts[10]. The upstream and downstream effects of this subsurface barrier modelled[11] showed that this barrier may facilitate the excess demands of pumping water from the aquifer with marginal decline in groundwater heads. This study helped to suggest ways to improve the groundwater potential of the region as well as to meet the irrigation needs and the increased water demand of MAPS.

Impact of agrochemicals

Fertilisers and pesticides applied to agricultural areas are a threat to groundwater quality in most parts of the world. So, it is important to study the movement of water along with the solute within the saturated zone. Migration of solute from the agricultural field as irrigation return flow through the saturated zone was studied in an intensively cultivated agriculture area in a part of the Palar and Cheyyar River basins (Fig. 1) during paddy cultivation[12]. Field studies were also conducted by collection of soil core samples during different times of fertilizer application. The movement of the solutes in the unsaturated zone was modelled using HYDRUS 2D. Model predicted results implied that the concentration of solutes in the soil zone was controlled by plant uptake, fertilizer application, infiltration and increase in irrigation return flow[12]. The concentration of nitrogen was controlled by denitrification and soil mineralization processes. Simulation was also carried out for a scenario wherein the amount of application of fertilisers was doubled. This showed increase in the concentration of chloride and nitrogen in soil. But the current level of fertilizer application was found not to affect the groundwater quality. This study enabled to understand the process of migration of solutes from the agricultural field to the saturated zone. Studies of this nature can be used to suggest the optimum amount of agrochemicals to be applied depending on the thickness of the unsaturated zone and the property of the chemical compound used.

Impact of uranium tailings pond

Regional radionuclide modelling

Identifying a proper location for waste disposal site is a complex and difficult task. There is always a possibility of contamination of groundwater because of percolation of the leachate from the wastes. There are several criteria that determine the location of a waste disposal site such as the time period of disposal, method, rate of dumping, amount and type of waste, moisture content, pH, climate, geology, drainage, rainfall characteristics, etc. In several locations of India, waste disposal sites are not engineered and waste is dumped on open ground or in excavations. Even in engineered landfills, there is a possibility of seepage of leachate. Hence, in order to assess the possible impact of waste disposal site on existing groundwater environment and to identify a suitable location, groundwater modelling can be used as an effective tool. One such study was carried out around a proposed uranium tailings pond at Seripalli in Nalgonda district, Telangana, India (Fig. 1) with a view to estimate its radiological impact[13].

Groundwater flow and radionuclide contaminant (^{238}U, ^{234}U, ^{230}Th and ^{226}Ra) transport modelling (FEFLOW) from the tailings pond was carried out with consideration of ingrowths of progenies. Model predicted that the radionuclides move very little from the tailings pond even at the end of 10,000 years due to their high distribution coefficients and low groundwater velocities[13]. The concentrations of these radionuclides in the groundwater were found to be considerably lower than their drinking water standards even at the nearest user point. These concentrations were translated into committed effective dose rates to the members of the public residing in the vicinity of the uranium tailings pond at different distances. The results indicate that the highest effective dose rate to members of the public through groundwater drinking pathway is 2.5 times lower than the drinking water guideline of 0.1 mSv/y even after a long time period of 10,000 years. Hence, the site was found suitable for dumping the wastes from uranium mining and milling activities.

Geochemical modelling

A geochemical modelling approach was also applied to the uranium mining and tailings pond area in Nalgonda district, Telangana (Fig. 1). This geochemical study using PHREEQC model concentrated only on the proposed tailings pond area. Objective of this study was to predict the optimum chemical composition of calcium, magnesium, sodium, potassium, chloride, sulphate, carbonate, bicarbonate, and uranium to be present in the wastes generated from milling activities which will be dumped on the ground surface so as to minimise the impact of these tailings waste on groundwater quality[14]. Also the desirable infiltration rate of the liners to be installed at the uranium tailings pond area was determined. This work included inverse as well as forward modelling. Inverse modelling aided to validate the geochemical processes identified by comparing with previous work carried out[15] for the same region. Forward modelling executed for a period of 100 years indicated an increase in the concentration of solutes in groundwater from the present background levels for a down-gradient distance of up to 500 m during the operation of the mines i.e. until 16 years[16]. After this period, the increased concentration of ions in groundwater was predicted up to 100 m from the tailings pond at the end of 100 years. Fig. 4 shows variation in the concentration of ions at different porosity. Real time application of the results of this study will help to preserve the groundwater quality around the tailings pond area. Similar approach can be adopted around landfill sites, ore processing and dumping areas etc.

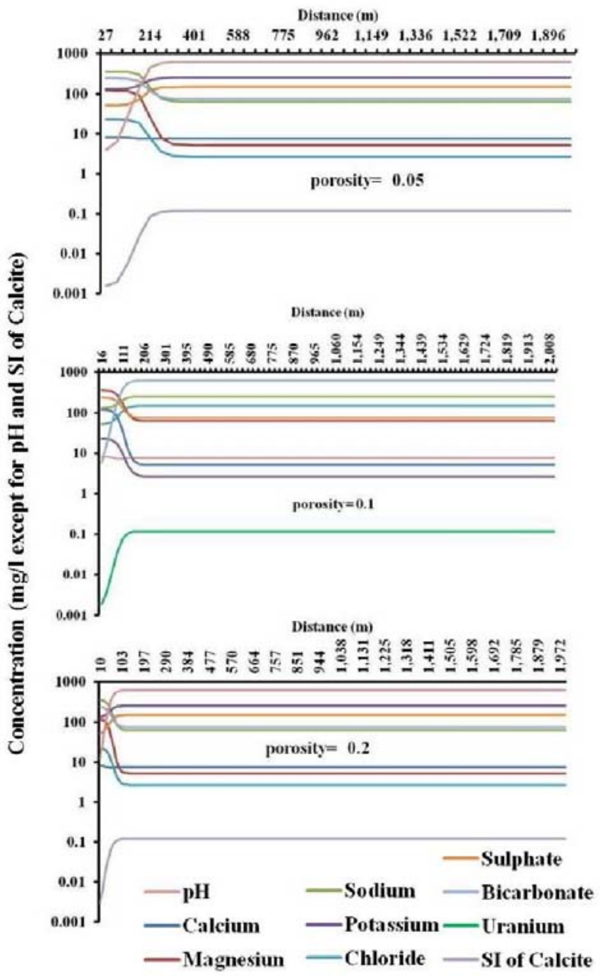

Fig. 4—Variation in the movement of ions at the end of 100 years at different porosity from a uranium tailings pond

Conclusion

Application of groundwater models to predict seawater intrusion along the coastal areas, pumping of seawater for a desalination plant, impact of natural disasters like the tsunami in 2004 on groundwater quality, impact of construction of sub-surface barriers to improve groundwater levels and prevent salinization of the aquifer, impact of use of fertilisers and pesticides on groundwater quality and their transport in the unsaturated zone in Tamil Nadu, radionuclide and geochemical modelling to predict the effect of a proposed uranium mining and tailings pond on groundwater quality of a region in Telangana are put forth in this manuscript. Apart from these, models have been used to resolve a variety of other groundwater problems. This manuscript provides an idea for employing models for diverse groundwater situations.

Acknowledgements

The results presented are based on projects funded by Department of Science and Technology (Grant: SR/S4/ES-21/Cauvery/P6), Board of Research in Nuclear Sciences, Department of Atomic Energy (Grant no. 2007/36/35), Department of Science and Technology's Funds for Improvement in Science and Technology scheme (Grant: SR/FST/ESI-106/2010), University Grants Commission's Special Assistance Programme (Grant: UGC DRS II F.550/10/DRS/2007(SAP-1)) of the Government of India. Authors are also thankful to the University Grants Commission's Centre with Potential for Excellence in Environmental Science (Grant: F.No.1-9/2002 NS/PE) for their financial support which helped in creating facilities to carry out part of these work.

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