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Comparative evaluation of numerical model and artificial neural network for simulating groundwater flow in Kathajodi–Surua Inter-basin of Odisha, India

S. Mohanty [a,*], Madan K. Jha [b], Ashwani Kumar [a], D.K. Panda [a]

[a] Directorate of Water Management, Bhubaneswar 751 023, Odisha, India
[b] AgFE Department, Indian Institute of Technology, Kharagpur 721 302, West Bengal, India

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SUMMARY

In view of worldwide concern for the sustainability of groundwater resources, basin-wide modeling of groundwater flow is essential for the efficient planning and management of groundwater resources in a groundwater basin. The objective of the present study is to evaluate the performance of finite difference-based numerical model MODFLOW and the artificial neural network (ANN) model developed in this study in simulating groundwater levels in an alluvial aquifer system. Calibration of the MODFLOW was done by using weekly groundwater level data of 2 years and 4 months (February 2004 to May 2006) and validation of the model was done using 1 year of groundwater level data (June 2006 to May 2007). Calibration of the model was performed by a combination of trial-and-error method and automated calibration code PEST with a mean RMSE (root mean squared error) value of 0.62 m and a mean NSE (Nash–Sutcliffe efficiency) value of 0.915. Groundwater levels at 18 observation wells were simulated for the validation period. Moreover, artificial neural network models were developed to predict groundwater levels in 18 observation wells in the basin one time step (i.e., week) ahead. The inputs to the ANN model consisted of weekly rainfall, evaporation, river stage, water level in the drain, pumping rate of the tubewells and groundwater levels in these wells at the previous time step. The time periods used in the MODFLOW were also considered for the training and testing of the developed ANN models. Out of the 174 data sets, 122 data sets were used for training and 52 data sets were used for testing. The simulated groundwater levels by MODFLOW and ANN model were compared with the observed groundwater levels. It was found that the ANN model provided better prediction of groundwater levels in the study area than the numerical model for short time-horizon predictions.

1. Introduction

Groundwater is an invaluable natural resource used for variety of purposes like domestic, agricultural and industrial uses. Almost all of the liquid freshwater in our planet (more than 98%) occurs as groundwater, while less than 2% occurs in the more visible form of streams and lakes which often are fed by groundwater (Bouwer, 2000; Russell, 2003). During the last few decades, groundwater has become an important source of freshwater throughout the world. It is estimated that groundwater provides about 50% of the current global domestic water supply, 40% of the industrial supply, and 20% of water use in irrigated agriculture (World Water Assessment Program, 2003). However, the aquifer depletion due to over-exploitation and the growing pollution of groundwater are threatening our eco-systems (Shah et al., 2000; Sophocleous, 2005; Evans and Sadler, 2008). The recent studies using GRACE satellite data have shown alarming decrease in groundwater levels in developing countries like India and Iran (Rodell et al., 2009; Voss et al., 2013). Hence, the key concern is how to maintain a long-term sustainable yield from aquifers (e.g., Hiscock et al., 2002; Alley and Leake, 2004).

The total annual replenishable groundwater resource of India is about 43 million ha m. However, in spite of national scenario on the availability of groundwater being favorable, there are pockets in certain areas of the country that face scarcity of water. This is because the groundwater development over different parts of the country is not uniform, being quite intensive in some areas (CGWB, 2006). Excessive pumping has led to alarming decrease in groundwater levels in several parts of the country like Gujarat, Tamil Nadu, West Bengal, Odisha, Rajasthan, Punjab and Haryana (CGWB, 2006; Mall et al., 2006). In studies using GRACE satellite data, it was found that the groundwater reserves in the states like Rajasthan, Punjab and Haryana are being depleted at a rate of

* Corresponding author. Tel.: +91 9438008253; fax: +91 674 2301651.
E-mail address: smohanty.wtcer@gmail.com (S. Mohanty).

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17.7 ± 4.5 km^3/year. The same data suggest that between August 2002 and December 2008, the region lost 109 km^3 of groundwater which is double the capacity of India's largest reservoir Wainganga and almost triple the capacity of Lake Mead, the largest man-made reservoir in the United States (Rodell et al., 2009). This in turn has increased the cost of pumping, caused seawater intrusion in the coastal areas and has raised questions about the future availability of groundwater.

In order to avoid the overdraft and declining groundwater level, it is important to understand the behavior of an aquifer system subjected to artificial stresses. Simulation modeling is an excellent tool to achieve this goal. Groundwater simulation models are useful in simulating groundwater flow scenarios under different management options and thereby taking corrective measures for sustainable use of water resources by conjunctive use of surface water and groundwater. During the last 20 years various studies have been taken up for groundwater flow simulation in different basins using MODFLOW and other models (e.g., Reichard, 1995; Onta and Das Gupta, 1995; Ting et al., 1998; Reeve et al., 2001; Lin and Medina, 2003; Rodriguez et al., 2006; Zume and Tarhule, 2008; Al-Salamah et al., 2011; Gaur et al., 2011; Xu et al., 2012). However, the physically based groundwater simulation models are very data intensive, laborious and time consuming. Empirical models generally require less data and less effort in comparison to physically based models (Coppola et al., 2005). Artificial Neural Network (ANN) models are one of such models, which are treated as universal approximators and are very much suited to dynamic nonlinear system modeling (ASCE, 2000). The ability to learn and generalize from sufficient data pairs makes it possible for ANNs to solve large-scale complex problems. A number of studies have been done on the application of neural networks for groundwater level forecasting (e.g., Coulibaly et al., 2001; Coppola et al., 2003; Daliakopoulos et al., 2005; Lallahem et al., 2005; Nayak et al., 2006; Uddameri, 2007; Krishna et al., 2008; Trichakis et al., 2009; Mohanty et al., 2010; Ghose et al., 2010; Yoon et al., 2011; Adamowski and Chan, 2011; Li et al., 2012; Nourani et al., 2012).

The performance of numerical models evaluation like MODFLOW and empirical models like artificial neural network (ANN) in forecasting groundwater levels has been reported by Coppola et al. (2003). In their study, a neural network model was developed for predicting water levels at 12 monitoring well locations screened in different aquifers in a public supply well field, Florida, USA in response to changing pumping and climatic conditions. The developed neural network model predicted the groundwater level more accurately than the calibrated numerical model at the same location over the same time period. Parkin et al. (2007) developed a hybrid approach of numerical modeling and artificial neural networks to assess the impacts of groundwater abstractions on river flows in hydrogeologic settings representing most of England and Wales. The artificial neural network model was trained using the input and output data from SHETRAN numerical modeling system and tested using a field data from a case study site. They demonstrated the successful application of the approach for modeling river–aquifer interactions and its potential for modeling more complex hydrological systems. Nikolos et al. (2008) evaluated artificial neural network as an alternate approach to groundwater numerical modeling to optimize pumping strategy of production wells located in the northern part of Rhodes Island in Greece. They concluded that the use of neural network as an approximate model can significantly reduce the computational burden associated with numerical model and can provide very close to optimal solutions. Banerjee et al. (2011) evaluated the prospects of artificial neural network simulation over 2-D solute transport model (SUTRA) in estimating safe pumping rate to maintain groundwater salinity in Kavaratti island of Lakshadweep archipelago. In the present paper, a groundwater flow simulation model has been developed using Visual MODFLOW, an empirical ANN model has been developed for forecasting groundwater levels and comparison between both models has been done. For this, a study area named Kathajodi–Surua Inter-basin has been selected within the Mahanadi deltaic system of Odisha, eastern India. The present study has innovative elements concerning the methodology of groundwater-flow modeling and the study area.

2. Study area

The study area is a typical river island within Mahanadi deltaic system of eastern India and is surrounded on both sides by the Kathajodi River and its branch Surua (Figs. 1 and 2). It is locally called as 'Bayalish Mouza' and is located between 85°54′21″ to 86°00′41″ E longitude and 20°21′48″ to 20°26′00″ N latitude. The total area of the river island is 35 km^2. The study area has a tropical humid climate with an average annual rainfall of 1650 mm, of which 80% occurs during June to October months. The normal mean monthly maximum and minimum temperatures of the region are 38.8° C and 15.5° C in May and December, respectively. The mean monthly maximum and minimum evapotranspiration rates are 202.9 mm and 80.7 mm in May and December, respectively. Agriculture is the major occupation of the inhabitants and groundwater is the major source of irrigation in the area. There are 69 functioning government tubewells in the area, which constitute major sources of groundwater withdrawals for irrigation. These tubewells were constructed and managed by the Orissa Lift Irrigation Corporation, Government of Orissa, India. Now, they have been gradually handed over to the local water users' associations. There is no water shortage during the monsoon season in the study area, but in the summer season, the farm ponds dry up and the groundwater from tubewells is not sufficient to meet the entire water requirement of the farmers.

The river basin is underlain by a confined aquifer which mostly comprises coarse sand. The thickness of the aquifer varies from 20 to 55 m and the depth of the aquifer from 15 to 50 m over the basin (Mohanty et al., 2012). The aquifer hydraulic conductivity varies from 11.3 to 96.8 m/day, whereas the values of storage coefficient range between 1.43×10^{-4} and 9.9×10^{-4}.

3. Materials and methods

3.1. Data collection and analysis

Daily rainfall data of 20 years (1990–2009) and daily pan evaporation data of 4 years (2004–2007) were collected from a nearby meteorological observatory at Central Rice Research Institute (CRRI), Cuttack, Orissa located at about 2 km from the study area. The river-stage data available at an upstream site named Naraj (Fig. 1) were collected from the office of Central Water Commission (CWC), Bhubaneswar, Orissa. The lithologic investigations at 70 sites over the study area were carried out by test drilling method by Orissa Lift Irrigation Corporation (OLIC) Office, Cuttack, Orissa. The lithologic data were collected from the OLIC Office and analyzed by drawing geologic profiles along different sections in the study area. These lithologic analyses along with other field data were used for developing a numerical groundwater-flow model of the study area.

Since no groundwater data were available in the study area, a groundwater monitoring program was initiated by the authors. Monitoring of groundwater levels in the study area was done by selecting nineteen tubewells distributed over the study area. The locations of nineteen monitoring wells are shown as red circles in Fig. 2. Weekly groundwater-level data at the nineteen sites