Simulation of Varada Aquifer System for Sustainable Groundwater Development

H. Ramesh[1] and A. Mahesha[2]

Abstract: Groundwater flow modeling has been used extensively worldwide with varying degrees of success. The ability to predict the groundwater flow is critical in planning and implementing groundwater development projects under increasing demand for fresh water resources. This paper presents the simulation of the aquifer system for planning the groundwater development of Varada basin, Karnataka, India using the Galerkin finite-element method. The government of Karnataka State, India is implementing the World Bank assisted project, "Jal Nirmal" for a sustainable development of the region, thereby ensuring a safe supply of drinking water to the northern districts of the state. Varada basin is one of the beneficiaries of the project in Haveri district. Field tests carried out in the study area indicate that the region is predominantly a confined aquifer with transmissivity and storage coefficients ranging from $5.787 \times 10^{-6}\ \mathrm{m}^2/\mathrm{s}$ ($0.500\ \mathrm{m}^2/\mathrm{day}$) to $4.213 \times 10^{-3}\ \mathrm{m}^2/\mathrm{s}$ ($3.640 \times 10^{2}\ \mathrm{m}^2/\mathrm{day}$) and $0.011-0.001 \times 10^{-2}$, respectively. This study mainly emphasizes the spatial and temporal variability of groundwater potential under different developmental scenarios. The model predictions were reasonably good with correlation coefficients ranging from 0.78 to 0.91 with the root mean square error of about 0.46–0.78 during calibration and validation. The stated accuracies are based on comparisons between measured and calculated heads. The outcome of the study would be a useful input for the conjunctive use of surface water and groundwater planning for the sustainable development of the region.

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CE Database subject headings: Calibration; Validation; Aquifers; Finite element method; Ground-water recharge; Sustainable development.

Introduction

Understanding the physics of groundwater flow and its interaction with surface water is a complex task. This is mainly because of the heterogeneity of the geo-hydrological formation, the complexity in the recharge processes, and the conditions at the boundary of the aquifer which is considered a system. The models are used to help establish locations and characteristics of aquifer boundaries and assess the quantity of water within the system and the amount of recharge to the aquifer (Anderson and Woessner 1992). Effective use of groundwater simulation codes as management decision tools requires the establishment of their functionality, performance characteristics, and applicability to the problems at hand (Paul et al. 1997). Thus the role of numerical models for the simulation of an aquifer is of utmost importance in the field of groundwater engineering. A comprehensive review of various models available for groundwater flow simulation can be found elsewhere (Kumar 2002). The finite difference and finite-element methods are known and have been used for the past several decades. However, the finite-element method allows more accurate simulations of boundary and flow direction in the model (Karlheiz and Moreno 1996) and variation of head within an element than other methods. For many groundwater problems, the finite-element method is found to be superior to the finite difference method (Willies and Yeh 1987). Heterogeneities and irregular boundary conditions can be handled easily by the finite-element method. This is in contrast to the difference approximations that require complicated interpolation schemes to approximate the complex boundary conditions. Moreover, the size of the element can be easily modified to reflect the rapidly changing state variables or parameter values in the finite-element method. The details on the theory of the above two methods and the solution techniques are well established and are beyond the scope of this paper.

The contribution of the groundwater system based on mass conservation considerations expressed in the hydrologic balance equation was stated by Todd (1959) in terms of specific yield. The maximum quantity of water that can be guaranteed from a groundwater system during the critical dry period is being defined by Sophocleous (1998) and Alley and Leake (2004) from the sustainability point of view. The objective of many groundwater resource studies is the determination of how much water is available for pumping; that is, determination of the maximum possible pumping compatible with stability of the groundwater supply. The management of aquifers in a river basin was studied by Sophocleous (2000) from the hydrologic perspective. He presented idealized examples of aquifer systems illustrating the usefulness of numerical models in generating their responses for induced recharge from surface water.

Miles and Rushton (1983) have developed a model to repre-

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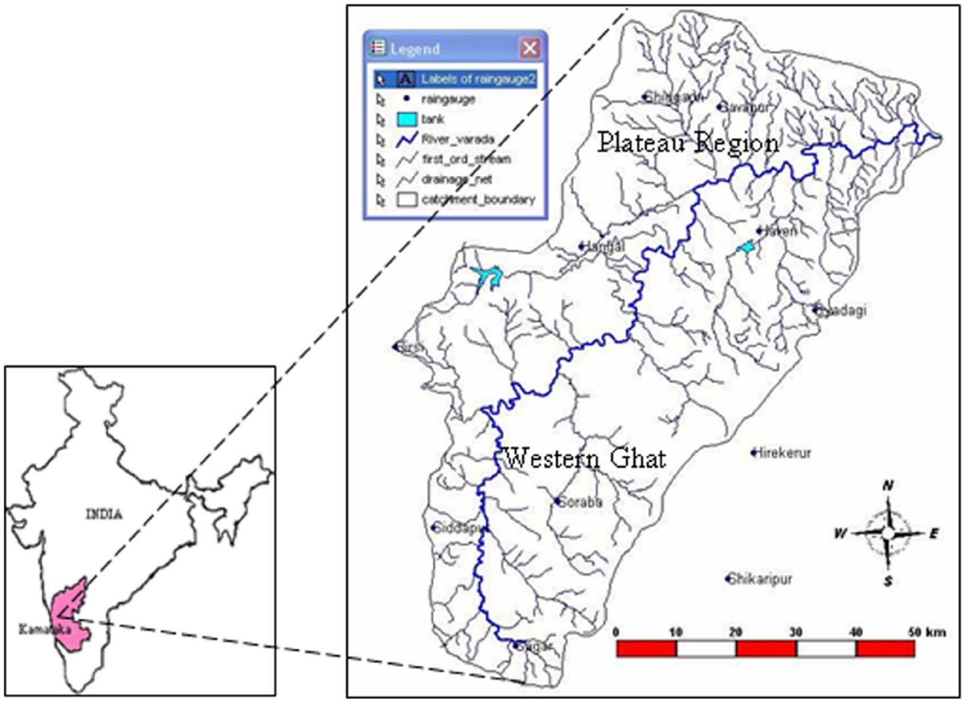

Fig. 1. Study area location

sent surface and subsurface flows for a catchment in central England. A finite difference model was used to represent groundwater flow in the aquifer with surface water flows by flow balance techniques. The results showed that the model flows simulated were quite accurate. Sarwar (1999) reported the performance of a finite-element model for an irrigated area in Pakistan in predicting the groundwater levels up to the year 2010 in response to pumpage and recharge scenarios. The study revealed that increase in pumpage from the present rate would further strain the groundwater resources. A geographical information system (GIS) linked groundwater flow model was developed by Ruud et al. (2001) to evaluate the system responses for various stress scenarios including the surface water recharge which played a vital role in the optimal utilization of the water resources of the basin. Both the preceding authors have accounted for the hydrological components such as evapotranspiration, pumpage, recharge due to rainfall, pond and tanks, canals, etc., in predicting the system response.

The state of the science of interaction between surface and groundwater was explained by Sophocleous (2002) and various authors elsewhere (Ozt et al. 2003). A study was conducted (Munoz et al. 2003) in the upper Santiago valley aquifer in Chile to determine the availability of water and long-range sustainable extraction rate. Water table depths were simulated using numerical models with information on recharge for 48 years under different extraction policies. The model showed that it was unable to supply groundwater demand on a sustainable basis. A simple groundwater balance model was developed (Peranginangin et al. 2004) based on 15–20 years of hydro-meteorological, land use, soil, and other relevant data to generate the hydro-geologic information needed for the water accounting procedure. The water accounting procedure was then used to evaluate present and potential future water use performance in the basin.

A regional surface water-groundwater model of the Yaqui valley, a 6,800 km^2 irrigated agricultural region located along the sea of Cortez in Sonora, Mexico was calibrated by Schoups et al. (2005). The results showed that the effect of including the process of bare soil evaporation was significantly greater than the effects of parameter uncertainty. The simulated water balance showed that 15–20% of the water that enters the irrigation canals was lost by seepage to groundwater. The main discharge mechanisms in the valley were crop evapotranspiration (53%), nonagricultural evapotranspiration and bare soil evaporation (19%), surface drainage to the sea of Cortez (15%), and groundwater pumping (9%). In comparison, the groundwater discharge to the estuary was relatively insignificant (less than 1%). A numerical model developed for groundwater flow in Thailand (Chuenchooklin et al. 2006) predicted that groundwater recharge during the flood and no flood periods were about 70–75% and 25–30% of annual recharge, respectively. The model also showed a high correlation between observed and simulated water levels.

Due to inadequate rainfall, groundwater has acquired a vital role in the development of Varada basin's agricultural economy. However, lack of awareness concerning the use of groundwater, either by itself or combined with surface water resources, has led to groundwater overexploitation. As a result, most of the places in the basin experience significant drawdown in groundwater levels. The objective of the present study is the development and application of a groundwater model in conjunction with a surface water model for sustainable development of the basin. The model considers the present and future demand for freshwater resources in predicting various scenarios of groundwater development. The results from the study would be useful for the development of an optimization model on the conjunctive use of surface water and groundwater resources of the basin which is underway.

Study Area

The Varada river basin lies between latitude 14–15° 15′ N and longitude 74° 45′ to 75° 45′ E in the Karnataka state, India

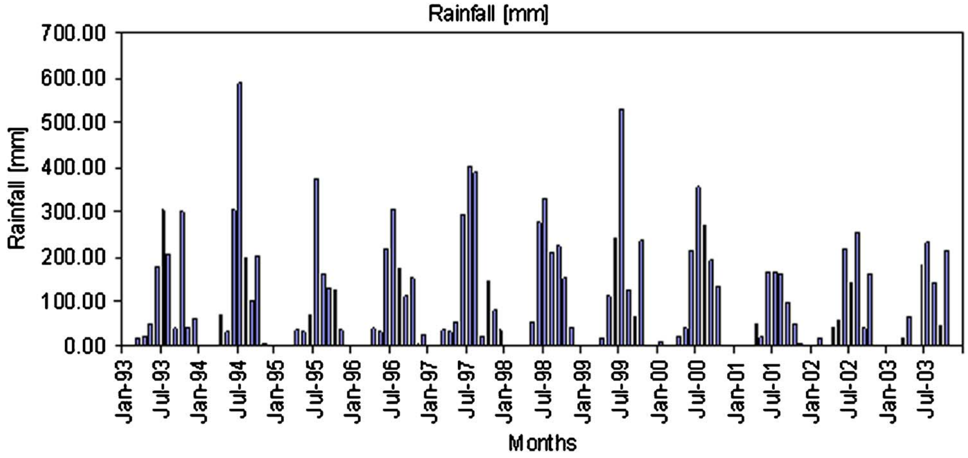

Fig. 2. Histogram of average rainfall for Varada basin

(Fig. 1). The river originates at Varadamoola at an altitude of 610 m above the mean sea level (MSL) in Sagar taluk (taluk is a subdivision of a district) of Shimoga district, Karnataka. It has a drainage area of about 5.020×10^9 m^2 and flows towards the north-east for about 2.200×10^5 m and joins the river Tungabhadra. Physiographically, the Varada basin consists of western ghats on the west and a plateau region in the east. The term "ghat" means mountainous forest range which runs parallel to the west coast of India at a distance of about 1.0×10^5 m from the seashore. The Varada River is a major tributary of Tungabhadra River which ultimately joins the river Krishna. Sirsi, Siddapur, Soraba, Sagar, and part of Hanagal taluks are covered by the western ghat region and form a dense tropical forest zone. The remaining area falls under the plateau region.

Climate

The climate of the Varada basin is humid to semiarid. The average temperature in the basin varies from a maximum of 34°C during the summer to a minimum of 18°C during the winter season. The south-west monsoon brings the bulk of the rainfall. Three seasons are identified for the region based on the distribution of rainfall. They are the premonsoon season from January to May, the monsoon season from June to September, and the postmonsoon season from October to December. In general, the normal rainfall over the basin varies from 2,070 mm in the western ghats to 775 mm in the plateau region. The typical rainfall pattern for the region is shown in Fig. 2. The rainfall data are available for 11 rain gauge stations from 1991 to 2003 and the Thiesson polygon network is formulated for the areal distribution of rainfall and recharge in the analysis.

Geology and Soil

In the Varada basin, lateritic soil, sandy loam, and black soil are found and the detailed characteristics are available elsewhere (NBSSLUP 1996). The black soil (clayey soil), also known as the black cotton soil, is seen forming extensive plains in the basin. The soil is characterized by the presence of montmorillonite which has the property of retaining moisture. The major soil types are moderately deep to very deep and well drained clayey soils. The aquifer is predominantly a confined aquifer with depth to hard strata varying from 150 to 250 m (Bhat et al. 1978; Siddaiah 1982; Jal Nirmal 2003). At isolated locations, semiconfined conditions were also observed. The average depth to groundwater level is about 8 m. The basin has about 50 observation wells. The basin is composed of igneous and metamorphic rocks and is weathered up to a depth of about 50 m. The nature of the weathered mantle is generally clayey in the case of gneiss and sandy in the case of granite. In addition to these, massive basalt, vesicular, and amygdoloidal rocks can be seen (Pattabhiramaiah 2001) at isolated locations.

Water Resources

Groundwater is the primary source for drinking, agriculture, and industrial purposes in the basin. Alluvial formations along the Varada River and it's tributaries serve as important groundwater reservoirs. Groundwater levels are essentially controlled by the type of rock, fracture patterns, physiographic features, and rainfall distribution in space and time. Primary porosity is almost absent in granite, gneiss, and schist formations. The weathered and secondary fractures are the only water bearing formations found in these rocks.

The development of groundwater in the state is through dug wells, dug-cum-bore wells, and bore wells. The sinking of bore wells, for both domestic and irrigation purposes is considered to be the cause for depletion of water levels. Utilization of groundwater resources is minimum where adequate surface water is available. Overexploitation of groundwater resources is reported in about 43 taluks. Out of these, groundwater exploitation, has exceeded 50% of the available groundwater resources in 29 taluks. The demand for drinking water in the urban and rural areas is bound to increase in the coming years. The periodical monitoring of wells for the period 1973–1996 shows a declining trend in groundwater levels. Areas showing a declining trend in groundwater levels are associated with a higher degree of groundwater development. At present, the number of bore wells existing in the basin is about 23,000 (Jal Nirmal 2003). In spite of deep drilling, the yield is considerably low due to the presence of hard formations.

The major river in the basin is the Varada river. A huge quantity of water goes unused during the monsoon without much utilization. The river is usually dry during January–May. The data pertaining to river yield are collected from the stream gauge sta-

Table 1. Recharge and Extraction Rates in Study Area

Year		January	March	February	April	May	June	July	August	September	October	November	December
1993	R	0.000	6.319	0.000	7.887	19.579	69.272	113.669	79.480	15.720	113.088	16.936	21.834
	Q	18.686	33.978	28.693	38.222	43.241	67.111	84.093	58.774	31.054	111.417	40.123	24.444
1994	R	0.000	0.925	0.000	26.016	12.508	118.605	220.435	75.127	38.581	76.609	3.494	0.000
	Q	23.032	19.890	20.064	20.237	31.221	92.854	178.586	57.781	30.412	74.430	8.981	11.343
1995	R	0.765	0.000	0.000	13.672	11.746	26.842	139.463	61.742	50.232	48.150	14.002	0.000
	Q	23.553	23.553	20.585	23.901	33.591	23.727	140.858	50.441	26.922	69.393	11.134	13.113
1996	R	0.000	0.000	0.253	16.041	12.831	86.096	113.550	65.618	43.667	57.656	3.430	9.940
	Q	23.380	23.901	23.669	24.479	29.793	66.782	143.326	49.512	26.905	69.152	11.933	14.271
1997	R	0.964	20.465	0.000	13.540	12.021	113.683	150.899	144.751	8.858	54.490	31.112	14.067
	Q	27.651	24.725	28.866	27.940	24.063	86.933	135.260	121.181	26.195	69.217	13.484	15.255
1998	R	0.000	0.043	0.000	0.773	20.054	106.213	124.111	78.942	87.554	56.789	16.355	1.089
	Q	26.262	27.824	28.113	23.310	24.461	82.940	124.837	90.390	61.572	66.671	13.675	13.964
1999	R	0.000	0.204	0.272	7.113	42.309	94.262	198.240	47.320	25.154	87.793	0.624	0.000
	Q	1.620	6.956	7.317	9.288	36.626	87.394	198.510	50.631	26.049	83.294	4.398	2.066
2000	R	3.419	0.000	0.024	9.115	14.854	82.696	133.848	100.467	74.707	49.942	0.796	0.399
	Q	1.420	6.629	6.968	9.410	11.126	77.130	126.933	101.333	64.415	40.380	4.745	2.453
2001	R	0.040	0.000	0.005	19.400	8.304	64.135	62.293	60.928	37.645	19.034	2.642	1.761
	Q	1.345	6.738	7.361	15.079	9.005	62.327	61.354	58.210	32.201	15.479	4.566	2.153
2002	R	0.000	7.529	0.229	16.978	21.890	84.350	52.894	95.295	14.990	60.596	0.623	0.033
	Q	1.588	8.229	7.520	13.740	11.020	76.521	55.316	93.720	13.645	57.584	4.688	2.309

Note: Q=pum page; R=recharge ($\mathrm{m^3/s}$).

tion at Hosaritti village. The average daily flow in the Varada River is computed as 37.04 $\mathrm{m^3/s}$ (3.2 million $\mathrm{m^3/day}$) based on the daily stream flow records from 1991 to 2003. Dharma reservoir is the only major surface water body that is located in the Hanagal taluk. It irrigates about $6.060\times10^7\ \mathrm{m^2}$ of land through a 8.600×10^4 m long canal. Other tanks irrigate less area due to silting problems. Farmers are mainly dependent on groundwater resources for irrigation and domestic purposes which are available throughout the year. A few lift irrigation schemes (about 65) utilizing about 0.431 $\mathrm{m^3/s}$ (13.6 million $\mathrm{m^3/year}$) of water irrigate about $3.784\times10^6\ \mathrm{m^2}$ land. There are about ten barrages across the Varada River at Kusunur, Arelakmapur, Honkan, Hosaritti, Karjagi, Neeralgi, Sangure, Naganure, Hiremellihalli, and Kunimellihalli villages utilizing about 0.449 $\mathrm{m^3/s}$ (14.15 million $\mathrm{m^3/year}$) of water to irrigate about $4.079\times10^7\ \mathrm{m^2}$ of agricultural land.

Domestic Water Demand

Forecast of population over the basin was done by considering census data for the period 1951–2001 (Office of the Register General of India). Considering average national growth of 2% per the year, the incremental increase method gives the nearest value for the population in 2021. Hence, the incremental increase method was considered in the present study. The average rate of water use in the study area is fixed at $1.1\times10^{-6}\ \mathrm{m^3/s}$ (95 L per capita/day) (Jal Nirmal 2003), involving both villages and municipalities. Accordingly, the projected population and the water demand of the basin in the year 2021 is estimated as 1.768×10^6 and 1.944 $\mathrm{m^3/s}$ (1.680×10^2 million/L/day), respectively.

Agricultural Water Demand

Agriculture is the main occupation in the Varada basin for about 70% of the population. Important crops grown here are rice, jowar, bajra, small millets, cotton, sugarcane, pulses, groundnut, and bananas. The major forest products are teak, eucalyptus, cashew, casuarinas, bamboo, soft wood, etc. (Shiva 1991). The major crop area and their production over the last 50 years indicate a mixed scenario without any definite trend. Agricultural water demand is projected in the range of 5–10% increase per year by considering the increase in groundwater extraction through tube wells and rivers for the period 1993–2002. The estimate of recharge and pumping in the basin on a monthly average basis during the period 1993–2002 is given in Table 1.

Methodology

Aquifer Characterization

Many aquifer test methods (Krusman and De Ridder 1990) are available to determine the aquifer properties. These aquifer test methods use drawdown and recovery data measured in observation wells (Theis 1935; Jacob 1963; Walton 1987). The tests could be either constant or variable discharge pumping. In this study, step drawdown pumping tests (Birsoy and Summers 1980) were carried out to estimate the aquifer properties. The step draw-

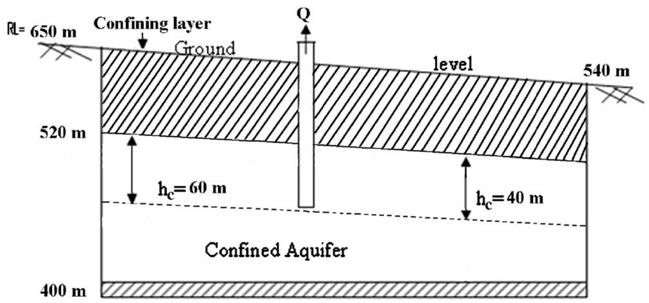

Fig. 3. Schematic diagram of confined aquifer

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Table 2. Water Balance Components for Period 1993–2003

Years	Recharge from rainfall (mm)	Recharge from water bodies (mm)	Canal recharge (mm)	Inflow into basin (mm)	Runoff +base flow (mm)	ET_c (mm)	Pumpage (mm)	Net recharge (R) (mm)	Recharge/ rainfall	Percent increase in pumping (%)
1993	1,200.59	61.28	30.64	2.45	367.54	596.70	98.49	232.23	0.19	0.00
1994	1,443.55	75.73	37.86	3.03	364.22	596.70	123.51	475.74	0.33	25.40
1995	968.67	48.47	24.24	1.94	263.91	596.70	134.61	48.10	0.05	36.67
1996	1,030.93	53.79	26.89	2.15	210.25	596.70	161.74	145.07	0.14	64.22
1997	1,487.62	74.68	37.34	2.99	242.84	596.70	183.60	579.49	0.39	86.41
1998	1,293.58	64.73	32.37	2.59	186.67	596.70	198.87	411.03	0.32	101.92
1999	1,270.48	66.60	33.30	2.66	241.17	596.70	188.25	346.92	0.27	91.14
2000	1,232.28	62.04	31.02	2.48	219.11	596.70	181.08	330.92	0.27	83.86
2001	713.05	36.32	18.16	1.45	80.61	596.70	164.54	−72.87	−0.10	67.06
2002	936.65	46.83	23.42	1.87	96.71	596.70	203.13	112.23	0.12	106.24
2003	902.14	45.41	22.70	1.82	85.76	596.70	207.05	82.55	0.09	110.22
Average	1,134.50	—	—	—	—	—	167.72	244.26	0.19	70.29

down tests were conducted for 8 h with 2 h each step. The drawdown was measured in the pumping well at specified time intervals using a digital water level recorder. Pumping test data were analyzed for 45 bore wells using the "StepMaster" (Step Master 1994) software and the storage coefficient and transmissivity are evaluated.

Conceptual Model

The basin is extensively covered by clayey soil (black soil) and hard rocks of varying thickness up to a depth of about 20–100 m. This soil is characterized with low hydraulic conductivity and forms the top confining layer. Below this, lateritic soil, sandy loam, and black soils along with the fractured rock form the productive aquifer. The above soils are moderately deep to very deep and well drained. Hard, massive rock formation consisting of gneiss and granite exists at a depth of about 150–250 m below the ground surface. The rock formation at the top is weathered and fissured up to a depth of about 50 m. The basin is a predominantly confined aquifer with semiconfined aquifers at isolated locations. The ground surface slopes from 650 m above MSL at the western end to 540 m above MSL at the outlet of the basin. Hence the thickness of confined aquifer varies from 80 to 120 m and an average thickness of 100 m is considered in the

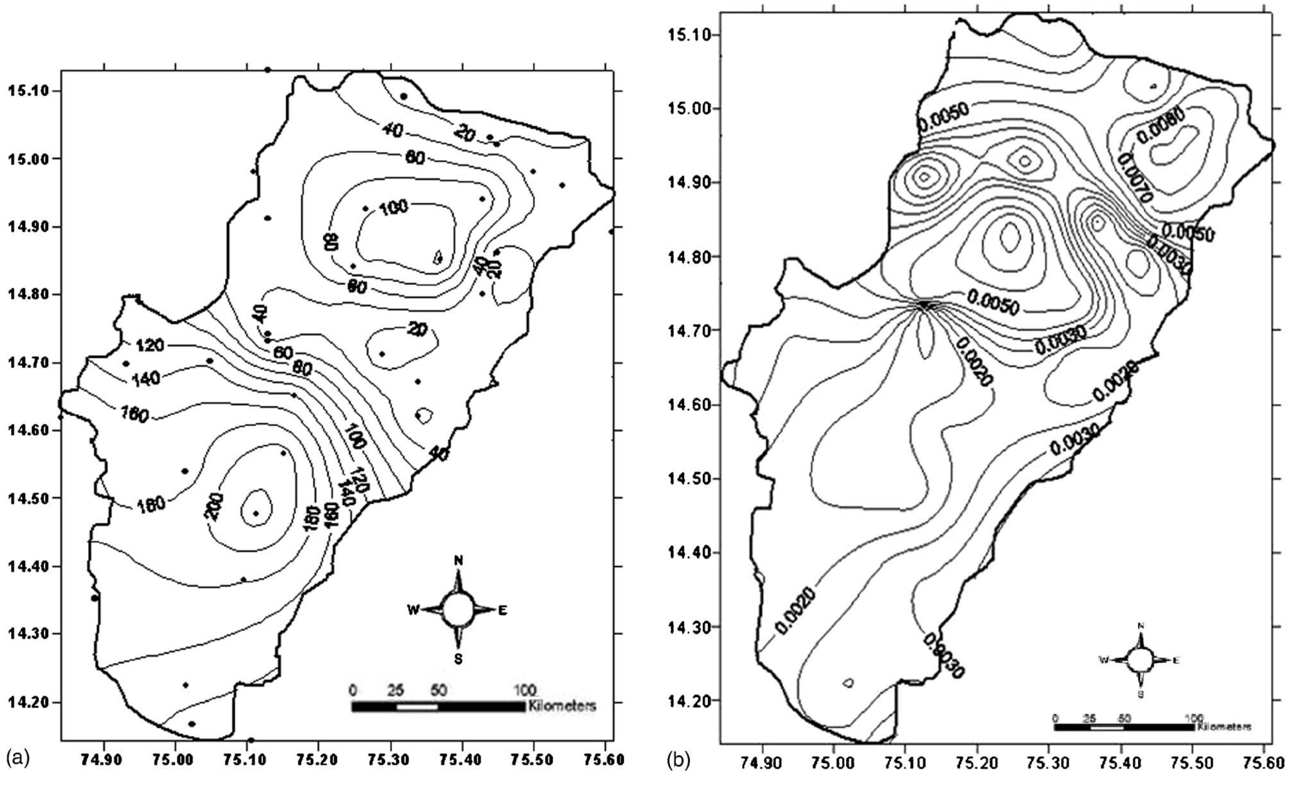

Fig. 4. (a) Transmissivity; (b) storage coefficient distribution map

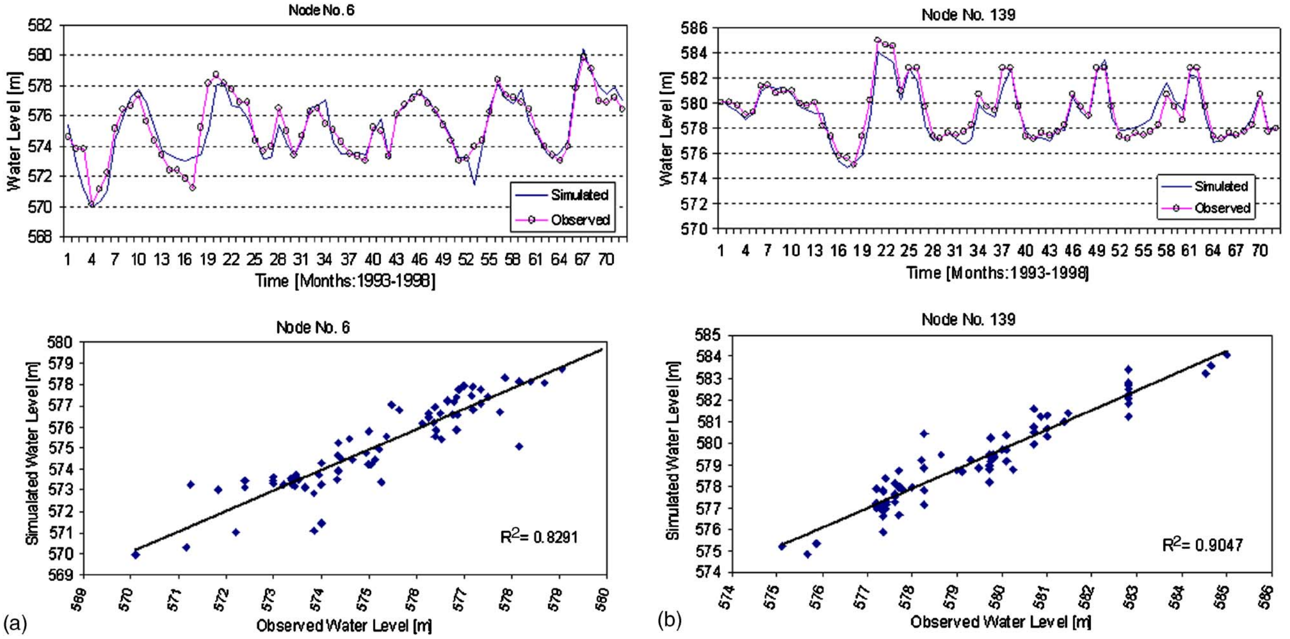

Fig. 5. (a) Observed and simulated groundwater levels during calibration; (b) observed and simulated groundwater levels during calibration

simulation. A schematic cross section of the aquifer is shown in Fig. 3.

The groundwater recharge in the basin is evaluated using a rainfall-recharge factor. This factor was evaluated using the Krishna Rao (Rao 1970) model which is extensively applied to south Indian basins, water balance model, and Ground Water Resource Estimation Committee (GEC 1997) studies. The net recharge was estimated from the algebraic sum of depth units of rainfall recharge, recharge from distributory and minors, recharge from water courses, recharge from link canals, inflow from adjacent basins, surface runoff, actual crop evapo-transpiration, evaporation from bare soil, and pumpage from the wells. The results from the water balance model are presented in Table 2. The water balance components are in depth units and are evaluated as per the guidelines given in Sarwar (1999) and GEC (1997). Average monthly values of meteorological data monitored by the India Meteorological Department (IMD) at Shimoga from 1931 to 1970 were used for the calculation of evapo-transpiration from the basin using CROPWAT (Martin et al. 1995). The year 2001 was found to be the year with the lowest rainfall and the recharge due to rainfall was only about 63% of the average value. Hence the net recharge in this year was estimated to be negative due to the outflow from the basin exceeding the net inflow. From the above methods, recharge as a ratio of rainfall

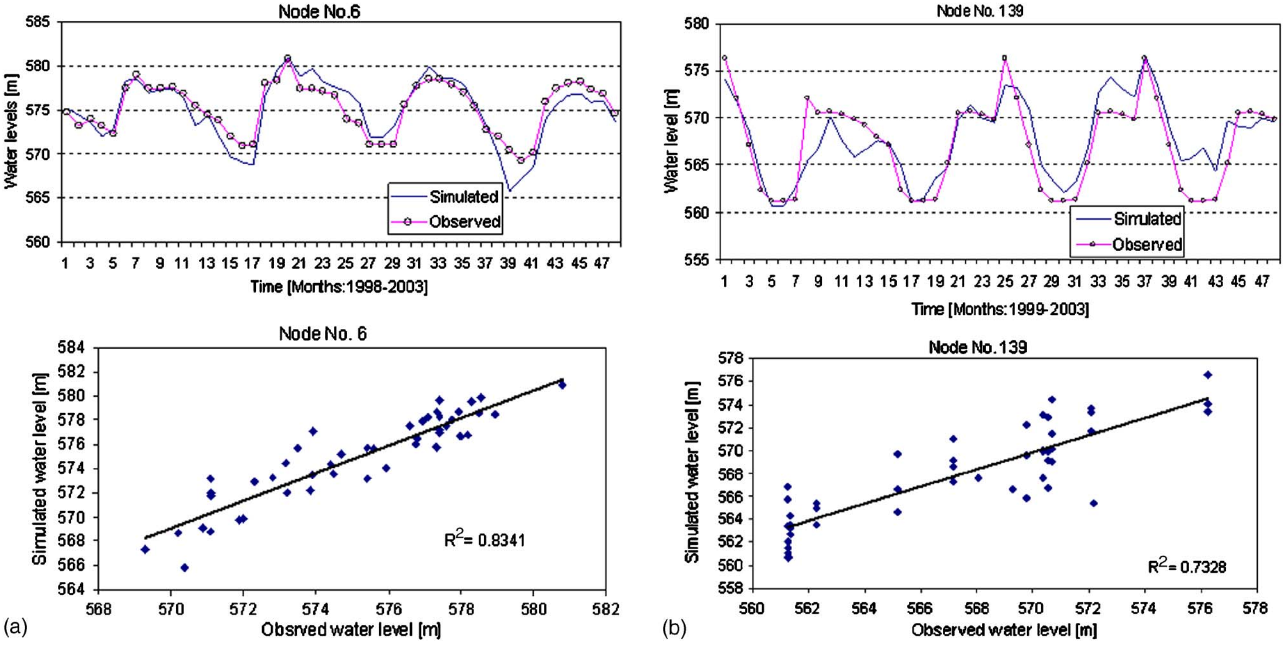

Fig. 6. (a) observed and simulated groundwater levels during validation; (b) observed and simulated groundwater levels during validation

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Table 3. Goodness-of-Fit Statistics between Observed and Simulated Piezometric Heads

Error measures	Well location (node number)						
	6	14	43	105	139	175	185
ME (m)	−0.08	−0.31	0.47	0.55	−0.21	−0.43	−0.08
RMSE	0.65	0.46	0.73	0.78	0.56	0.76	0.69
R^2	0.83	0.89	0.89	0.89	0.91	0.78	0.86

was estimated as 0.17–0.20. In the present study, a constant recharge factor of 0.2 was considered. The average rainfall in the basin was calculated by the Thiesson polygon method and the groundwater recharge due to rainfall was estimated for each polygon. The primary mechanism for recharge is through uplands recharge, river leakage, and leakage through semiconfined conditions spread over the entire basin. The river leakages are considered at the appropriate locations in the model. The annual average recharge in the basin is estimated to be about 32.503 m^3/s (1.025×10^3 million m^3/year).

The transient groundwater flow equation for confined aquifers (Jacob 1950) is solved using the Galerkin finite-element method (Pinder and Gray 1976; Huyakorn and Pinder 1983). The Neuman (flux type) boundary conditions are imposed along the boundary. The inflow into the basin was estimated at a few locations (Node Nos. 40,50,111,131,140,149,159,182,191, and 192) based on the hydraulic gradient across the boundary. The outflow from the basin was estimated near the basin outlet (Node Nos. 160 and 189). The flux across the boundary was calculated using Darcy's law. The rest of the boundary was assumed to be with zero flux. The groundwater levels of January 1993 were used as the initial condition. The basin was discretized into 329 triangular elements with 196 nodes having finer discretization in the western ghat region and coarser mesh in the plateau region. Nodes were assigned for the observation wells to calibrate and compare the results with the water level recorded. In the present study, an implicit scheme with $\theta = 1/2$ (Crank–Nicholson scheme) was adopted, which is unconditionally stable. The model was operated on a monthly basis to suit the availability of data. A tolerance limit of 0.001 was adopted to check the convergence during the solution process. A computer code was developed in the visual C++ for the entire process. The results are presented in GIS (ArcView) platform (ESRI 2004) for better visualization.

Table 5. Proposed Pumping and Recharge Rates for Scenario 1 (m^3/s)

Months	Recharge rate	Pumping rate				
		2003	2007	2008	2009	2010
January	0	10.147	10.900	11.679	12.485	13.320
May	21.890	11.245	11.872	12.528	13.214	13.931
September	14.990	13.244	13.952	14.693	15.469	16.281

Results and Discussion

Hydrogeology

The step drawdown tests were conducted in the Varada basin for 8 h with 2 h each step. The pumping test data were analyzed for 45 bore wells using the "StepMaster" software (Step Master 1994). The wells are driven up to a maximum depth of 180 m and the static water level observed was between 2.6 and 58.5 m below the surface. The estimated safe yield of the wells ranges from 1.417×10^{-3} m^3/s (85 L/min) to 6×10^{-3} m^3/s (360 L/min). As per World Bank norms, for a well to be successful, the yield should be more than 0.833×10^{-3} m^3/s (50 L/min). A wide range of transmissivity is observed in the basin ranging from as low as 7.52×10^{-6} m^2/s (0.65 m^2/day) to as high as 4.19×10^{-3} m^2/s (3.618×10^2 m^2/day). It is also observed that in most cases the storage coefficient in the Varada basin varies from 0.011 to 0.001×10^2 which confirms that the aquifer is predominantly confined. The transmissivity and storage coefficient contours of the Varada basin are shown in Fig. 4(a and b), respectively. The transmissivity distribution indicates that the aquifer is having higher values toward the western region indicating greater potential for groundwater. The plateau region is a relatively poor aquifer with lower transmissivity values. The storage capacity of the aquifer was found to be greater towards the north-east direction indicating greater potential for groundwater storage.

Model Calibration

In the present study, the trial and error calibration procedure is adopted. Initially, the aquifer parameters such as T and S are assigned based on the field test results. The simulated and measured values of piezometric heads were compared by adjusting the model parameters to improve the fit. The recharge components were varied within the range identified for the region.

Table 4. Mass Balance Calculations of Model during Validation Period (1999–2002)

Time step	Initial storage (million m^3)	Net influx (million m^3)	Net change in storage (million m^3)			Percent error [{Total − Net influx}/Initial storage] × 100 (%)
			Western region	Plateau region	Total	
2	—	−17.517	−23.390	6.756	−16.634	0.020
10	—	11.649	12.481	27.340	39.821	0.660
20	—	−2.262	−2.230	−14.956	−17.186	−0.350
30	4.234×10^3	4.671	10.050	−5.248	4.802	0.003
40	—	8.379	11.370	−15.440	−4.070	−0.290
48	—	−5.916	−8.051	−6.440	−14.491	−0.200
Average	—	—	—	—	—	−0.026

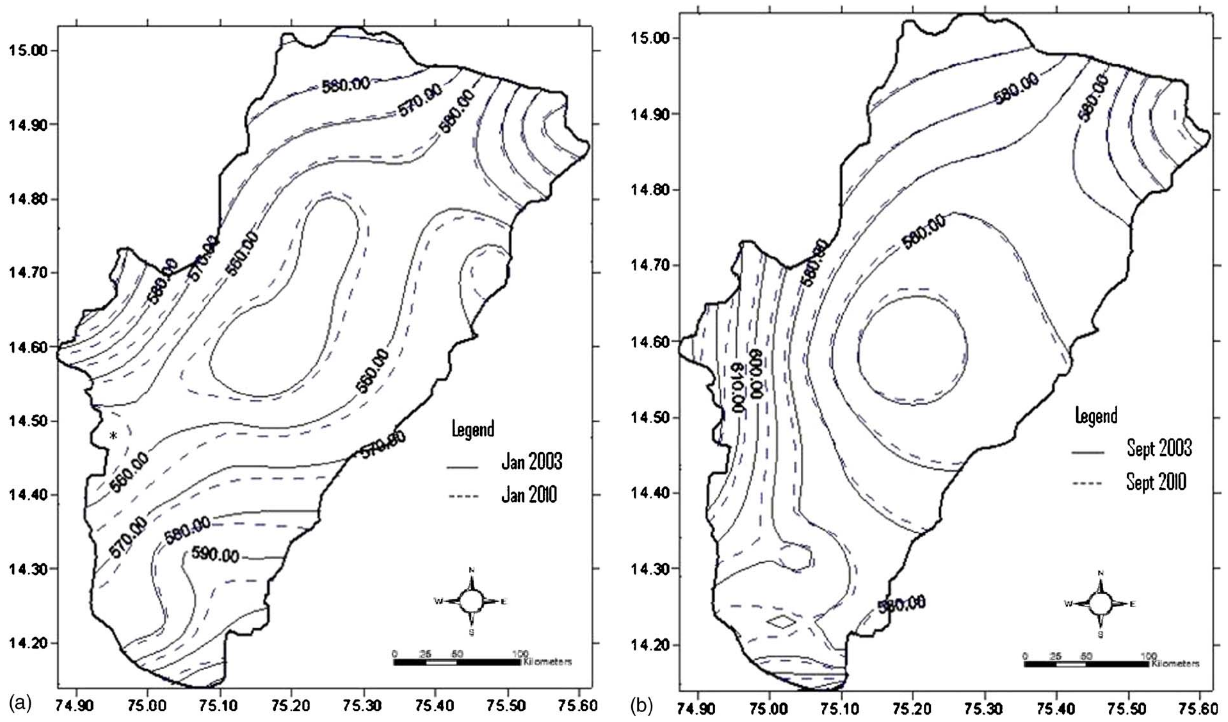

Fig. 7. (a); (b) Predicted groundwater level contour for January and September

The calibration was carried out for the period January 1993–December 1998. The study area has two distinct hydro-geological formations with transmissivity ranging from 5.787×10^{-6} to 1.389×10^{-3} m^2/s ($0.5-0.120\times10^3$ m^2/day) for plain area and 9.259×10^{-4} to 4.213×10^{-3} m^2/s ($80-364$ m^2/day) for the western ghat region. A number of trial runs were made by varying the transmissivity (T) and storage coefficient (S) values within the above specified range so that a reasonably good match was obtained between the computed and observed water levels. Forty five observation wells were selected as the fitting wells after considering their data availability and distribution in the region. The calibrated transmissivity values for the western ghat and the plateau region were found to be 1.736×10^{-3} m^2/s (150 m^2/day) and 1.157×10^{-3} m^2/s (100 m^2/day), respectively. The calibrated storage coefficient values for the western ghat zone and the plain area zone were found to be 0.025×10^{-1} and 0.063×10^{-1}, re-

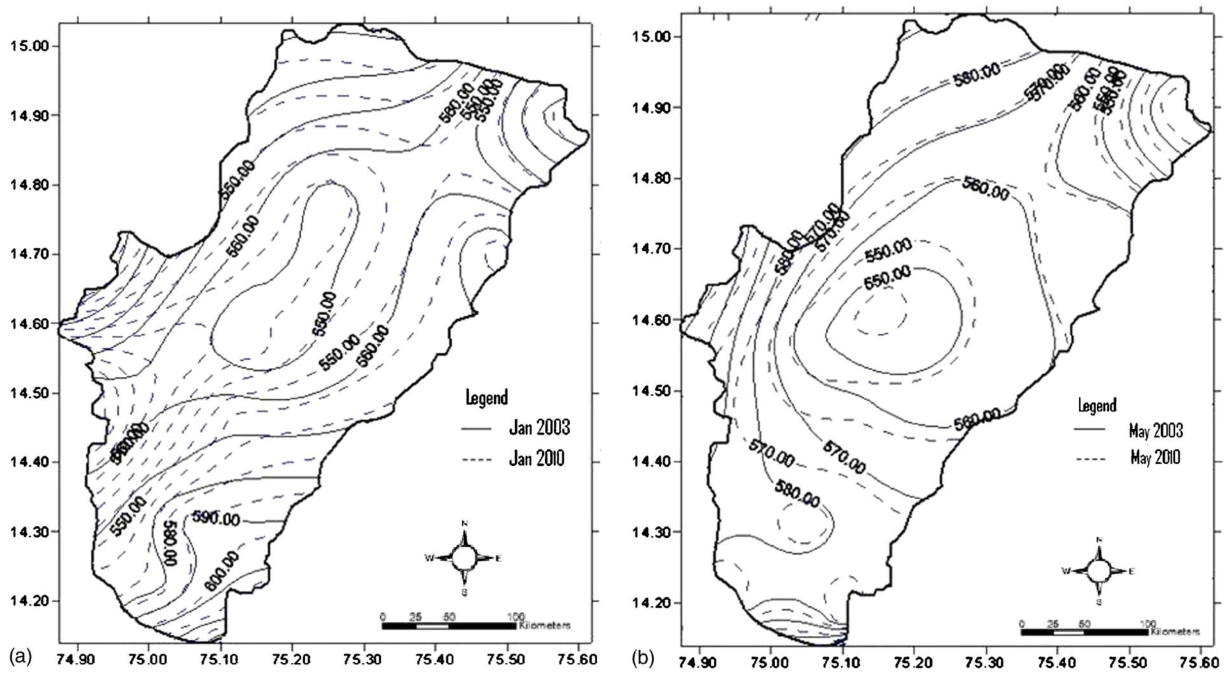

Fig. 8. (a); (b) Predicted groundwater level contour for January and May

Table 6. Proposed Pumping and Recharge Rates for Scenario 3

	2% increase in recharge (R) with 5% increase in pumping (Q) (m^3/s)									
	2003		2007		2008		2009		2010	
Months	R	Q	R	Q	R	Q	R	Q	R	Q
January	0.00	10.19	0.00	10.88	0.00	11.69	0.00	12.50	0.00	13.31
May	21.88	11.23	22.34	11.92	22.81	12.50	23.26	13.19	23.73	14.01
September	16.32	13.19	16.67	14.01	17.01	14.70	17.36	15.51	17.71	16.32

spectively. The computed and observed well hydrographs for a couple of observation wells are presented in Figs. 5(a and b), respectively.

The computed well hydrographs for the selected boreholes (seven) across the basin show a fairly good agreement with the observed values. The minor deviations could be attributed to the variation in the pumping pattern and insufficient bore well data. Nearly 10% of the total bore wells are unauthorized and hence pumping rate and pattern differ from the official data.

Model Validation

The objectives of the model performance analysis are to quantify how well the model simulates the physical system and to identify the problems, if any, in the model. The method typically used to quantify model error is to compute the difference between the predicted and the observed values of piezometric heads (residual) at the measuring location. The scatter diagrams, together with computed coefficient of determination, indicate where the discrepancies occur or general agreement occurs between the predictions and observations (Karlheiz and Moreno 1996). The performance of the calibrated model could be quantified by a number of statistics comparing the observed and simulated hydraulic heads (ASTM 2004). The following measures of the goodness-of-fit between measured and simulated water levels were calculated in this study:
mean error

$$\mathrm{ME} = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i) \tag{1}$$

root-mean-square error

$$\mathrm{RMSE} = \left[\sum_{i=1}^{N}\frac{(P_i - O_i)^2}{N}\right]^{1/2}\left[\frac{100}{\bar{O}}\right] \tag{2}$$

where P=simulated value; O=observed value; $\bar{O}$=mean observed value; and N=number of observations.

The groundwater levels simulated by the model were compared with the observed levels at the same locations for the period January 1999–December 2003 [Figs. 6(a and b)]. The hydrographs indicate that simulated levels match the observed values reasonably well. At some locations, however, the agreement was not up to the expectations (R^2=0.7). The simulated water levels were generally within 0.5 m of the recorded level.

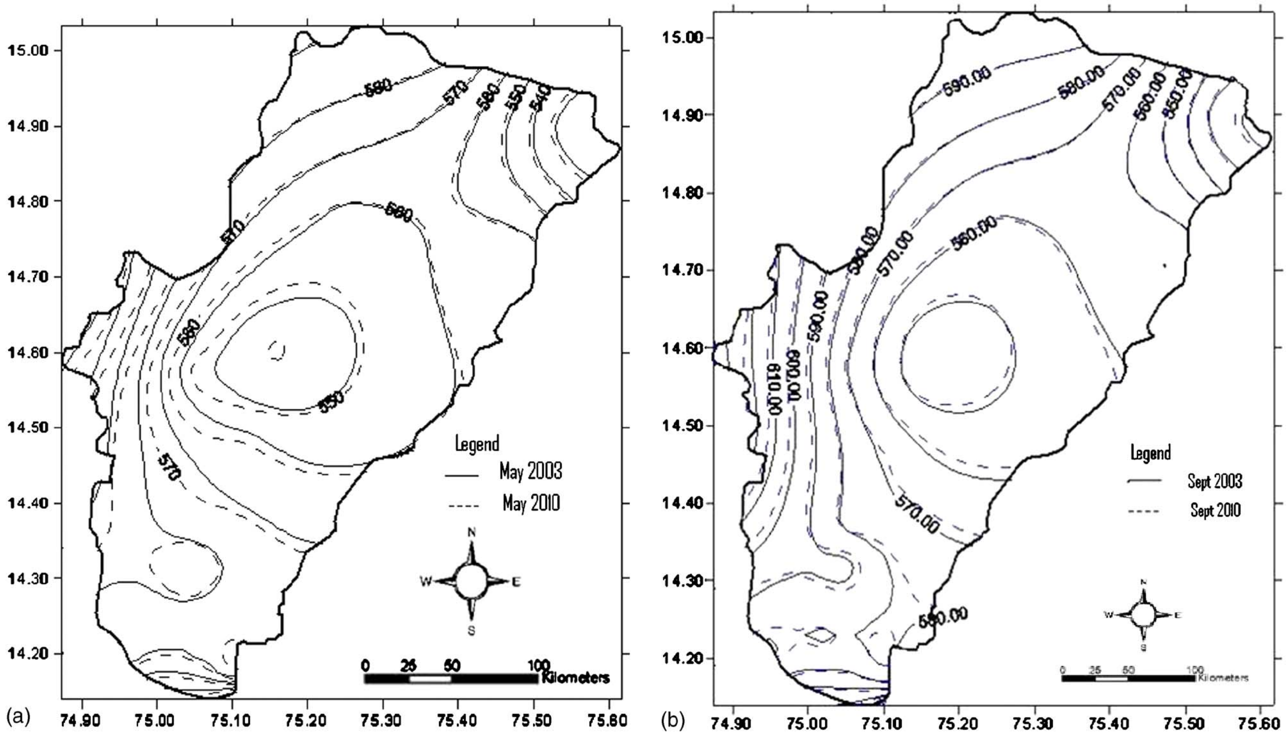

Fig. 9. (a); (b) Predicted groundwater level contour for May and September

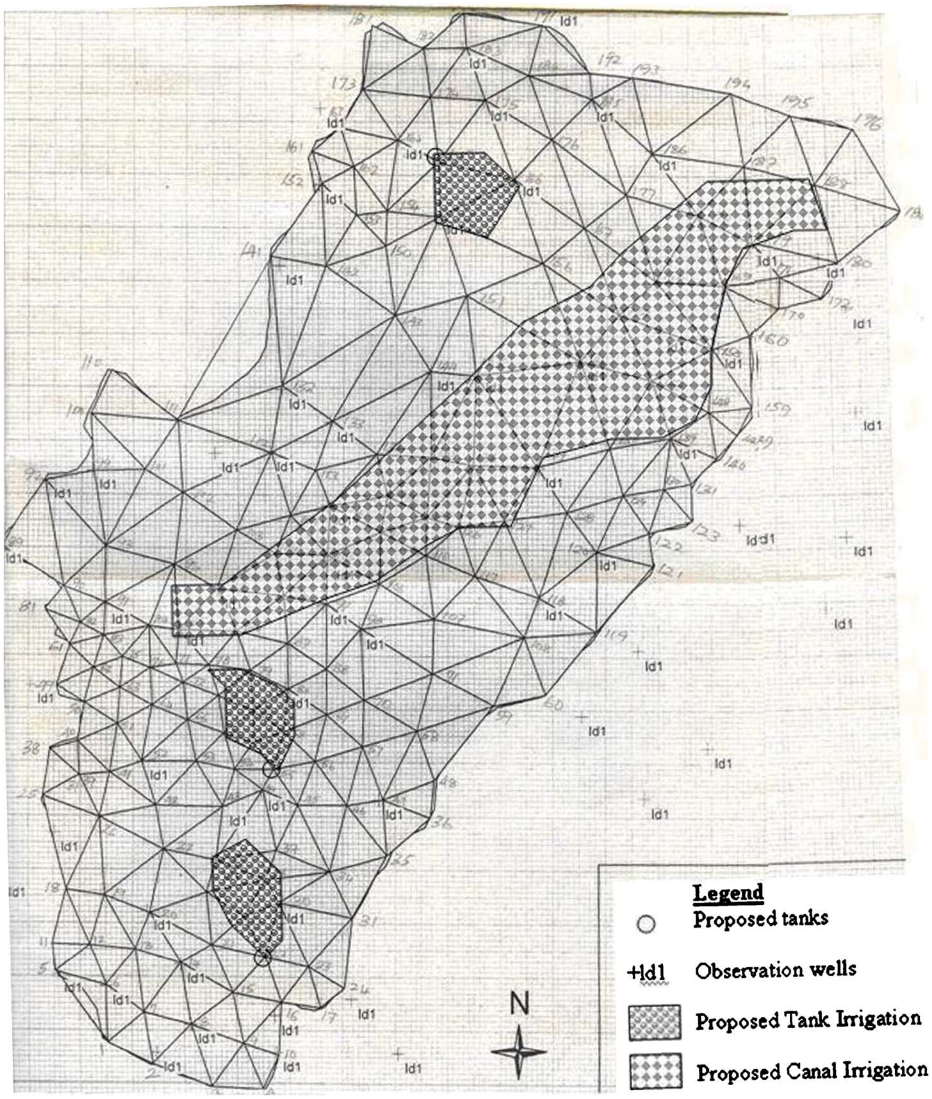

Fig. 10. Proposed canal, irrigated area, and tanks under Bedti-Varada link

The error parameters, generally used for evaluating the calibration quality (Frey Berg 1988; Anderson and Woessner 1992; Madan et al. 1996) for the observation wells are tabulated in Table 3. An examination of the spatial distribution of these errors showed that faster decline of groundwater level was found near the eastern and north-western boundaries of the study area, where no flow boundary was imposed. This is due to the fact that a large number of bore wells are located near these boundaries. The model performance was further tested through mass balance (Konikow and Bredehoeft 1978) calculations during the validation period (Table 4). The error observed was less than 1% and hence the numerical solution can be assumed to be quite accurate.

Model Application

The concept of sustainability development gained prominence during the past couple of decades which is centered around the idea of limiting the resource use to the levels that could be sustained over the long term involving the withdrawals from groundwater storage during dry periods that are balanced by replenishment during intervening wet periods (Alley and Leake 2004). However, the sustainability in a true sense involves the development of groundwater without causing unacceptable environmental, economic, or social consequences. The role of hydrologists in ascertaining the sustainability may be limited to providing information regarding the water level decline, reduction in the available storage, and its effect on the adjacent basin (Alley and Leake 2004). A series of such analyses can portray long-term effects caused by different scenarios of groundwater development on the management of water resources. The criterion adopted for the sustainability in the present work is based on the depletion of water level and the yield of the well based on the recharge capability as prescribed by the World Bank (Jal Nirmal 2003). As per the norms, the well yielding below $8.330 \times 10^{-4}\ \mathrm{m^3/s}$ (50 L/min) is treated as a failure. The corresponding groundwater levels observed in the field were less than half of the average thickness of the aquifer (<50 m). Considering this and the average annual recharge in the basin, the drawdown stabilizing at less than half of the aquifer thickness (50 m) is assumed to be sustainable in the present study.

Water demand (domestic and agricultural) in the Varada basin mainly depends on the groundwater resources since there is no significant surface water storage except for the Dharma reservoir.

The calibrated model was used to predict the groundwater resources in the region for various developmental activities over the period 2003–2010. The available data on rainfall and pumping rate were analyzed for the last 11 years (Table 1). It clearly indicates that there is an increase in the pumping rate by about 7% every year. Similarly, the years 1994 and 1997 may be considered as wet years with an increase in rainfall by more than 10% and a decrease in pumping rate by about 20%. Severe deficiency in rainfall (about 40%) occurred in the year 2001 with a gradual increase in pumping rate by about 10%. Based on these, the following probable developmental scenarios are considered.

Scenario 1

In this case, pumping rate is assumed to be increasing by 5% every year from the year 2003 considering the increase in domestic and agricultural demands. It is assumed that the recharge rate is constant beyond the year 2003. The monthly average recharge and abstraction are given in Table 1 for the period 1993–2002. The proposed rates of abstraction considering 5% increase per year are given in Table 5. The abstraction rate was maximum during the monsoon period due to the agricultural activities compared to winter (January) and summer (May) periods.

The predicted groundwater levels during winter (January) and monsoon (September) seasons are shown in Fig. 7. The system is sustainable without significant drawdown or groundwater mining, especially during the monsoon. However, during winter, the area around Tyagali village was prone to faster depletion of the groundwater level compared to other places. This may be attributed to a large number of unauthorized bore wells leading to more pumping.

Scenario 2

Based on the statistics (Dept. of Agriculture 2006) of increase in population and expansion of culturable land, it could be presumed that the maximum increase in the abstraction is about 10% every year. Accordingly, the groundwater levels are predicted between the years 2003 and 2010 [Figs. 8(a and b)]. Significant variation could be observed in the groundwater contours between the above years. The monthly abstraction rate in this case touches 19.757 $\mathrm{m^3/s}$ during the monsoon. The maximum drawdown noticed in the months of January, May and September over the period of 7 years is about 42.03, 25.96, and 29.16 m, respectively. At a few locations, dewatering of the aquifer occurs. However, in general, the system may be considered as sustainable with this rate of extraction since at most of the locations the drawdown stabilizes at a level greater than half of the thickness of the aquifer. As a conservative estimate, the sustainability of the system was tested for an increase in the extraction rate on the higher side (i.e., 20% increase/year) of the possible development. The model predicted aquifer dewatering at several locations during the planned period. Hence an alternate supply needs to be planned for this rate of development for sustainability.

Scenario 3

The average normal rainfall in the basin is about 2,070 mm in the western ghat and 775 mm in the plateau region. The year 2003 being the year with below average rainfall, above average or even normal rainfall would reduce the water demand. Also, numerous recharge structures are being implemented in the basin under the World Bank aided watershed development program (Jal Nirmal 2003) and 2–5% increase in the groundwater recharge would be a possible scenario. The proposed abstraction and recharge rates are shown in Table 6. The predicted groundwater levels for the months of May and September are shown in Fig. 9. The predicted contours indicate that the system is almost in equilibrium as in Scenario 1. The aquifer is capable of supplying water with the proposed rate even with deficient rainfall without significant depletion. This indicates that the current (2003) production level with possible increase at this rate would be sustainable for the region.

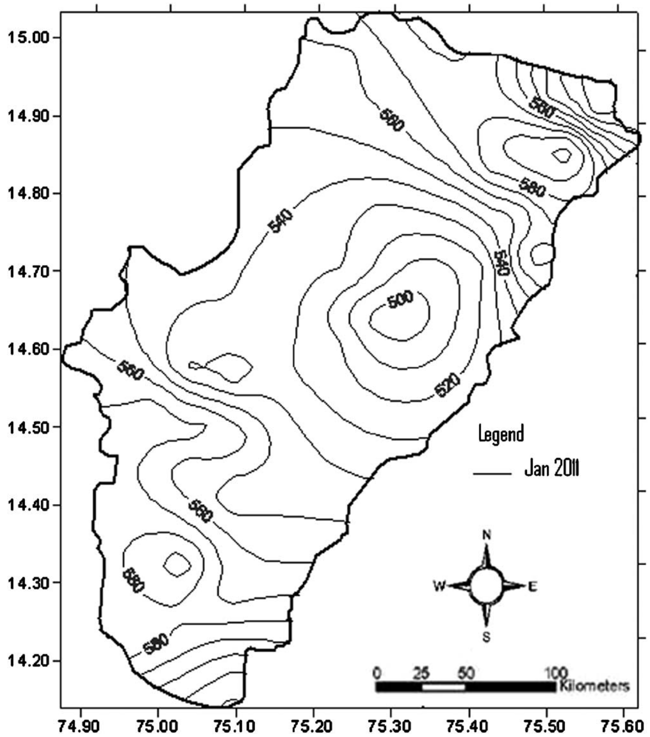

Fig. 11. Predicted groundwater level contour under Bedti-Varada irrigation scheme

Scenario 4: Interlinking of Rivers (Bedti-Varada Rivers)

In this case, the interlinking of west flowing river Bedti to east flowing river Varada was considered. The Government of India has proposed the scheme of interlinking of rivers in India. Bedti and Varada link is one of the peninsulars interlinking Indian rivers. This link proposal envisages diversion of 242 million $\mathrm{m^3}$ of surplus water of Bedti basin to Tungabhadra subbasin, to be utilized under Tungabhadra Project Command. The irrigation proposed under the link canal is 6.020×10^8 $\mathrm{m^2}$ in the drought prone Raichur district of Karnataka. In the present study, an attempt was made to utilize about 20% of diversion water in the Varada basin development. In this connection, the groundwater levels are simulated by considering an input of 60.5 million $\mathrm{m^3}$ as recharge through the proposed canal link and three tanks in the Varada basin. There is an increase in groundwater recharge of 15.97 $\mathrm{m^3/s}$ (1.38 million $\mathrm{m^3/day}$) (GEC 1997) due to an additional irrigable area. These areas are marked in Fig. 10 and the relevant nodes are identified. The model predicts a significant increase the groundwater level with this proposed scheme compared to 2003 [Fig. 8(a)] as shown in Fig. 11. Under this scheme, the groundwater level was estimated to be increased by about 10–15 m

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around the proposed irrigable areas compared to Scenario 2 (10% increase in growth rate per year) from the year 2010.

Conclusions

In this study, an attempt was made to simulate the Varada aquifer system to predict its response to various stress scenarios. Field tests indicate that the aquifer is predominantly confined in nature with transmissivity and storage coefficient values ranging from $5.787 \times 10^{-6}\ \mathrm{m^2/s}$ ($0.5\ \mathrm{m^2/day}$) to $4.213 \times 10^{-3}\ \mathrm{m^2/s}$ ($0.364 \times 10^{3}\ \mathrm{m^2/day}$) and $0.011 - 0.001 \times 10^{-2}$, respectively. The numerical solution was effective and accurate enough to simulate the aquifer system with mean error of $-0.43 - 0.55$ m and correlation coefficient from 0.78 to 0.91. Based on the statistics of the agricultural and domestic demands and rainfall distribution, several possible groundwater developmental scenarios have been predicted. It was appropriate to consider up to 10% increase in the groundwater extraction rate every year which was found to be sustainable. Dewatering of the aquifer was predicted for growth rates greater than the above limit and was not found to be sustainable. In addition, due to several recharge structures being planned for the basin under the World Bank scheme, the system would be further augmented. The Bedti-Varada link system would enrich the groundwater resources along the proposed canal network and around the storage reservoirs in the basin. The results from the study would be useful for planning the developmental activities in the basin with the conjunctive use optimization of surface and groundwater resources, the work of which is now in progress.

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