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Groundwater modelling for the assessment of water management alternatives

Ajay Singh *

Agricultural and Food Engineering Department, Indian Institute of Technology, Kharagpur, West Bengal 721 302, India

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SUMMARY

Rise in groundwater level followed by waterlogging and secondary salinisation has become a serious problem in canal irrigated areas located in arid and semi-arid regions of the world. To solve the problem, the groundwater model SGMP was applied in a waterlogged area of Haryana State of India in which about 500,000 ha has already waterlogged resulting in reduced crop yield and abandonment of agricultural lands. After successful calibration and validation, several scenario building exercises have been conducted. Error and sensitivity analyses of the model parameters were done. The impact of potential policy changes on the groundwater levels has been analysed through the model. The alternative scenarios revealed that small increase in the net recharge would cause the waterlogging problem to aggravate. On the other hand, if net recharge decreases, the situation would turn favorable. The study also revealed that by reducing the recharge in the range of 5–20% from the average values, the watertable could be stabilized at a safe depth. To prevent the area from further salinisation some recommendations can be given such as; increase in groundwater abstraction, water distribution as per water requirements of crops, and the lining of surface irrigation systems. Thus it is apparent that the SGMP model seems to be an effective tool for groundwater simulation. It has the potential of assessing the watertable behaviour due to various interventions. The results of simulation studies of existing and proposed water management policy, therefore, may form the basis for the identification of appropriate water management plans for the future.

1. Introduction

Irrigation is essential for sustainable crop production in arid and semi-arid regions, because annual precipitation is not sufficient to fulfil the crop water demand (Ji et al., 2007; Singh and Panda, 2012a). However, the agricultural intensification and specialization have resulted in declining biodiversity and other environmental problems in agro-ecosystems (Foley et al., 2005; Tilman et al., 2002). For instance, more than one-third of the world's irrigated land is affected by secondary salinisation, sodicity, and/or waterlogging (Heuperman et al., 2002). In India, alone, 8.4 million ha are affected by soil salinity and alkalinity, of which about 5.5 million ha are, waterlogged (Singh et al., 2012).

The threat of irrigation-induced soil and groundwater salinisation is increasing and becoming a major concern for food security and environmental conservation (Singh et al., 2010; Wichelns and Oster, 2006). Currently, some serious environmental problems exist in the central and western parts of Haryana State of India in terms of salinity development and waterlogging (Groundwater Cell, 2010; Singh, 2012a,b,c), because conventional agriculture was not traditionally associated with conservation and sustainable resource management. During the last four decades, most of the canal irrigated areas of Haryana are facing rising groundwater levels, and problems of waterlogging and soil salinisation are emerging (Boumans et al., 1988; Singh and Panda, 2012b; Singh, 2010). It is estimated that about 500,000 ha of the State is waterlogged.

To solve the waterlogging and salinity problems, one approach is to identify critical areas responsible for disproportionate amount of the groundwater recharge and to implement best water management practices such as reduction in canal water supply (Chowdhury, 1998), distribution of canal water based on spatially distributed crop water requirements (Kumar and Singh, 2003) and use of saline groundwater in conjunction with canal water (Malash et al., 2008; Minhas et al., 2007; Rhoades et al., 1992; Singh and Panda, 2012c; Singh, 2012d) in the identified critical areas. However, evaluation of the alternative management strategies only through field experiments is not feasible, because specific recommendations derived from site-specific field experiments cannot be generalised to regional level with different ecohydrological conditions. Moreover, to conduct field experiments for all ecohydrological conditions is expensive, laborious and time consuming, particularly if they should be representative for a sequence of years. In recent decades, with the advance of high-speed electronic computers, researchers developed versatile simulation models to analyse environmental and water use issues. These models by way of their predictive capability are often the only viable means of providing input to management decisions, and can help

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* Tel.: +91 3222281335/9434706472; fax: +91 3222255303.
E-mail addresses: erajay07@yahoo.co.in, ajay@agfe.iitkgp.ernet.in

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to forecast the likely impacts of a particular water management strategy. In recent years, a large number of agro-hydrological models (Konukcu et al., 2006; Xie and Cui, 2011; Xu et al., 2011) have been used for the groundwater and salinity management. These models have gained wide spread acceptance as effective tools to assess the impact of agriculture on ecosystems and environmental conservation. Prior to this assessment, these models need to be properly calibrated and validated using geo-hydrological data of the area concerned. Suitable alternative management options were then implemented for the management of water resources and agricultural sustainability.

This study analyses weather, crop, soil, and irrigation, with their representative parameters. In this context, a case study is conducted for an irrigated area (92,000 ha) located in Rohtak–Jhajjar districts of Haryana State (India). The Standard Groundwater Model Package SGMP (Boonstra and de Ridder, 1990; Boonstra, 1998) is applied to quantify the hydrological variables for all 'nodes' in the area. The model was evaluated under saline shallow watertable conditions using spatial information for the period 1997–2010. The best management strategies have been recommended considering the impact of potential policy changes on the future groundwater behaviour.

The present study is a follow-up of a previous study (Singh, 2011), in which different alternatives to waterlogging and salinisation were analysed along with the baseline conditions (1974–2009). The approach was to consider what would have happened, in comparison to the unaltered baseline conditions, had a given alternative been implemented. While, in the present study, the impact of different management scenarios on future (next 10 years) groundwater behaviour are evaluated with the help of a groundwater model SGMP.

2. Materials and methods

2.1. Study area

The State of Haryana is located in the northwestern part of India and covers a total area of 44,212 km^2, of which about 98% lies in an alluvial plain between the Ghaggar and Yamuna rivers. Nearly all the cultivable land in the State is under rice-wheat dual cropping system, which requires more water than is available by precipitation. As a consequence, groundwater development in some districts is more than the replenishable ground water recharge and a large part of the north, east and south Haryana (except central and western part) is facing the problem of falling groundwater table. However, in the study area, watertable is rising, as it is characterised by a geological and topographical depression in the centre which causes groundwater movement toward its centre. In the State, the groundwater level is primarily declining in areas with fresh and marginal quality groundwater. In contrast, rising groundwater tables are registered in areas where groundwater is of poor quality. Within the State there can, thus, be significant local variation in water management problems, with declining aquifers, waterlogging and salinisation existing side by side (Abrol, 1999; Bhalla, 2007; Datta and de Jong, 2002).

My study area lies between 28°30′N to 28°54′N latitude and 76°27′E to 76°54′E longitude and covers an area of about 92,000 ha. The area, which lies within the districts of Rohtak (24,783 ha) and Jhajjar (67,217 ha), is bounded by the Diversion Drain No. 8 flowing from North to South, which continues as Najafgarh Drain in a southeastern direction and the Dulehera Distributary bounding the area in an eastern direction (Fig. 1).

The study area features semi-arid climatic conditions with an average annual rainfall of 566 mm, about 75% of which is received from the southwest monsoon during July–September. The mean monthly climatic characteristics are shown in Fig. 2. The area is part of the older geological formations of India, which consists of slates, quartzite, sandstone, limestone, phyllites, and micaschists. The soil texture in the area is mainly of sandy loam to fine loam with clay content between 11% and 17%. The hydraulic conductivity of the unconfined aquifer material ranges between 4.7 and 11.2 m/day, and the saturated thickness ranges between 30 and 34 m. Specific yield varies from 0.09 to 0.23, and total soil porosity varies between 0.43 and 0.53 (Groundwater Cell, 2011). Cropping systems are commonly divided into two principal crop seasons, *kharif* (*monsoon*, July–October) and *rabi* (*winter*, November–April). Wheat is the major crop of the region, grown in winter season and covers about 81% of the net cropped area. Rice is the second major crop which is grown in monsoon season. Millets, sorghum, sugarcane, cotton, barley, mustard, pulses, and vegetables are also cultivated.

2.2. Model description

Several features like availability of data, software support, and capability and reliability of model for long-term predictions are the deciding factors regarding the selection of the software. In this study, the Standard Groundwater Model Package SGMP (version 2.7) (Boonstra and de Ridder, 1990; Boonstra, 1998) is used to analyse water balances of the study area. The SGMP is mainly used to predict the long-term impacts of management measures on groundwater levels. The model uses seasonal water balance components as input data, which are related to the surface and aquifer hydrology. Because of high amounts of input data required for calculation, only two seasons (*monsoon* and *winter*) from a given year is used in this study. Each individual season is termed as a *timestep* in the model. Day-to-day water balances are not considered for the following reasons: (i) it is very difficult to collect daily data, (ii) the model is designed to make long-term simulations, and (iii) because of high variability in daily data, long-term simulations are more reliable than short-term simulations.

The spatial variations in the model are accounted for through a network of *polygons*. The polygonal network is constructed on the basis of the given nodal coordinates using the Thiessen method. In the present study, the whole study area is divided into 44 square nodes, each of 2.5 cm × 2.5 cm size on a scale of 1:183,000 (Fig. 3). The nodal network thus formed provides 1–6 observation wells to complete a total of 68 observation wells for the whole area. Nodal network has two types of nodes, the external, and the internal. The external nodes are the boundary conditions, which act as a *head-controlled boundary* for the internal nodes. The model can also simulate flow-controlled and zero-flow boundaries. For the convenience, there is a provision in the model that the centroid of the each nodal area is taken as the representative of the whole area. All the recharge and discharge activities taking place in each nodal area are considered to be occurring at that centroid. Each node is treated as a separate groundwater unit, and data related to watertable elevation, natural surface level, hydraulic conductivity, and specific yield of the aquifer for each node is given as an input to the model.

The two-dimensional movement of groundwater through porous earth material is described by the following *partial-differential equation* which is based on Darcy's law and the equation of conservation of mass.

$$\frac{\partial}{\partial x}\left(KD\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(KD\frac{\partial h}{\partial y}\right)=-N \tag{1}$$

where $K(x, y)$ is the hydraulic conductivity of the aquifer (m/d); $D(x, y, t)$ is the saturated thickness of the aquifer at time t (m); $h(x, y, t)$

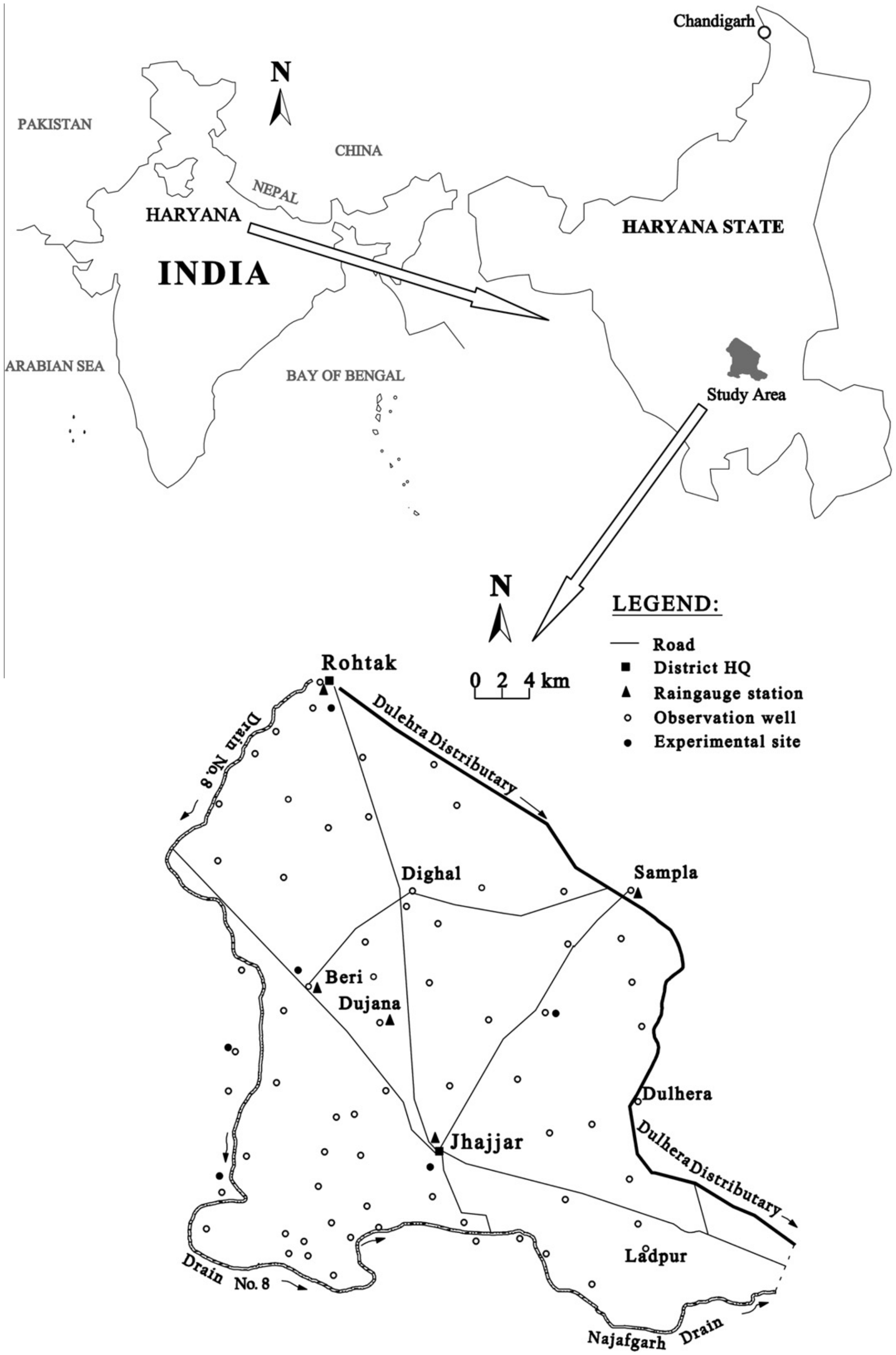

Fig. 1. Location map of the study area with rain gauge stations and observation points.

is the hydraulic head in the aquifer at time t (m); and $N(x, y, t)$ is the source or sink term at time t (m/d).

The left-hand side of Eq. (1) represents the horizontal flow in the aquifer, and the right-hand side represents the vertical flow. The vertical flow (N) consists of different flow components, depending on the type of aquifer. For an *unconfined aquifer*, N is the total of three terms.

$$N = R - P - S_y \frac{\partial h}{\partial t} \tag{2}$$

where $R(x, y, t)$ is the net rate of recharge (m/d); $P(x, y, t)$ is the net rate of abstraction (m/d); S_y is the specific yield (dimensionless); h (x, y) is the hydraulic head in the aquifer at time t (m); and t is the time (d).

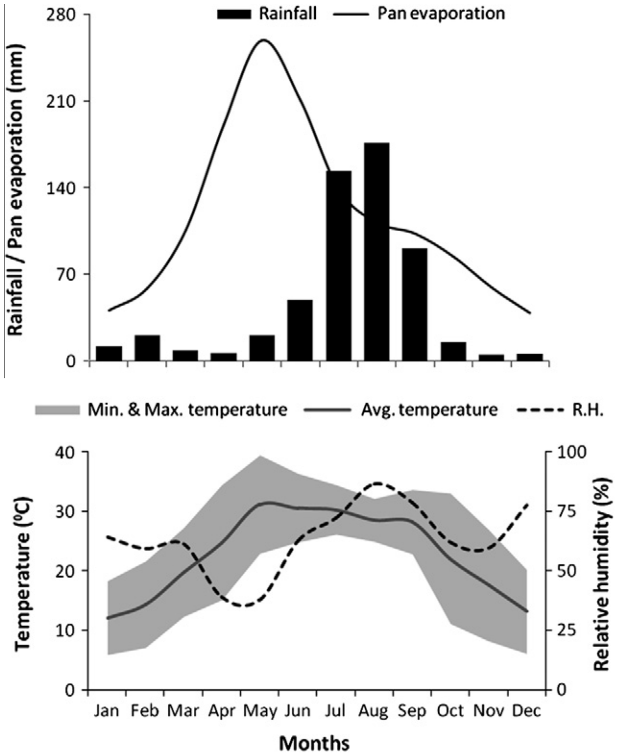

Fig. 2. Distribution of mean monthly climatic characteristics.

The solution to the partial differential Eq. (1) is obtained by using *finite difference method*. In this method, the study area is discretized in space into small but finite intervals. Each sub-area, thus formed is designated as a nodal area. For an arbitrary node n of a nodal network, the equation for an *unconfined aquifer* is given as (Boonstra and de Ridder, 1990):

$$\sum_i (h_i - h_n)\frac{W_{i,n}K_{i,n}D_{i,n}}{L_{i,n}} = -A_nR_n + A_nP_n + A_nS_{yn}\frac{dh_n}{dt} \qquad (3)$$

where $W_{i,}n$ is the length of side between nodes i and n (m); $L_{i,n}$ is the distance between nodes i and n (m); and A_n is area associated with node n (m^2).

2.3. Data acquisition

An overview of the collected regional information and its sources in the study area are provided in Table 1.

2.4. Net groundwater recharge

The nodal net groundwater recharges were calculated for each season to estimate groundwater fluxes. This net recharge constitutes various recharge and discharge components, such as rainfall; seepage from main canals, distributaries, minors, and watercourses; field irrigation losses; and pumping from tubewells. The details about the estimation of different recharge and discharge components are given in Singh (2011).

2.5. Model calibration and validation

Before a model can be used for studying the long-term impact of various water management scenarios on the watertable, it needs to be calibrated and validated for a number of years. Calibration of model was done following the standard procedure (Sorooshian and Gupta, 1995).

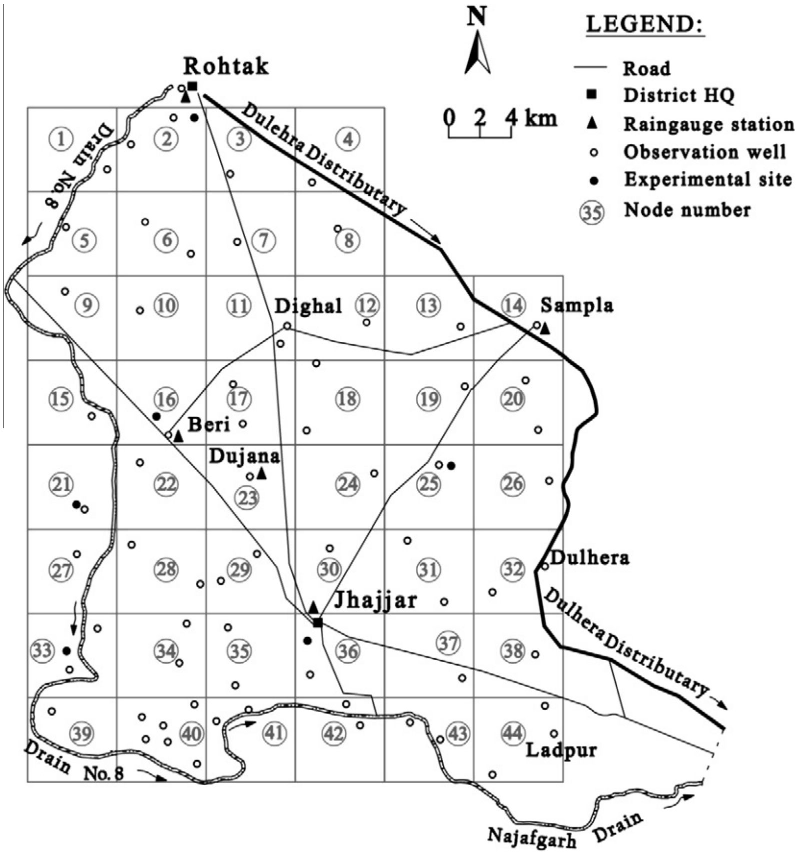

Fig. 3. Nodal network for SGMP model.

Table 1
Overview of the collected regional information and its sources.

Data	No. of stations/ locations	Period (years)	Source/organization
Rainfall	5	36 (1975–2010)	Raingauge stations at Rohtak, Jhajjar, Beri, Dujana, and Sampla
Climatic parameters	1	42 (1969–2010)	India Meteorological Department, Pune
Groundwater level	68	13 (1997–2010)	District Hydrologist, Rohtak
Number of tubewells, and their locations (village wise)	–	21 (1989–2010)	District Hydrologist, Rohtak
Aquifer properties	11	5	District Hydrologist, Rohtak
Daily discharge of canals	–	13 (1997–2010)	Irrigation Department, Rohtak and Jhajjar
Total, net sown, and irrigated area under different crops	–	13 (1997–2010)	Department of Agriculture and Tehsildar's Office, Rohtak, and Jhajjar

The model was calibrated for the period October 1997–June 2002, which was subsequently validated with observed watertable data for October 2002–June 2010. The calibration was achieved by adjusting a number of spatially distributed and sensitive soil hydraulic input parameters such as hydraulic conductivity (K) and specific yield (S_y). These parameters were determined by the Groundwater Cell (2011) by analysing the time-drawdown data from pumping tests. The calibration and validation was done for each node.

2.6. Sensitivity analysis

The main objective of a sensitivity analysis is to understand the influence of various model parameters on the aquifer system and to identify the sensible parameter(s). In the present study, the sensitivity analyses were performed for the sensitive model parameters i.e., K and S_y. A 50% increase and decrease of the calibrated parameters were assigned to assess the sensitivity (Ting et al., 1998).

2.7. Evaluation of model performance

In order to evaluate model performance, error statistics can be used to quantify the differences in the calculated and observed groundwater levels. In this study, mean error (ME), root mean square error (RMSE), and model efficiency (EF) were used.

$$\mathrm{ME} = \frac{1}{N}\sum_{i=1}^{N}(O_i - P_i) \tag{4}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - P_i)^2} \tag{5}$$

$$\mathrm{EF} = \frac{\sum_{i=1}^{N}(O_i - O)^2 - \sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - O)^2} \tag{6}$$

where N is the total number of the observations, O_i is the observed groundwater level of the ith observation, P_i is the predicted groundwater level of the ith observation, and O is the mean of the observed groundwater levels (i = 1 to N).

3. Results and discussion

3.1. Calibration and validation results

Results of the model calibration and validation for six arbitrarily chosen nodes (i.e., nodes 7, 10, 17, 23, 29, and 36) are presented in Figs. 4a–f and 5a–f. This can be seen that the predicted values reasonably match with the observed ones; this is also confirmed by the high regression coefficients of 0.87, 0.91, 0.87, 0.92, 0.91, and 0.97 during calibration, and 0.79, 0.91, 0.88, 0.80, 0.78, and 0.96 during validation period, respectively. The calibration and validation was equally successful for other nodes as well, with regression coefficients between 0.77 and 0.97 during calibration, and 0.64–0.98 during validation period (Tables 2 and 3). Further, Tables 2 and 3 show that the mean error (ME) and root mean square error (RMSE) for almost all the nodes during calibration and validation are reasonably low. The model efficiency (EF) (Eq. (8)) evaluates the error relative to the natural variation of the observed values and varies from $-\infty$ to 1.00. When the square of errors between the predictions and observations is as large as the variation of the observations, then EF becomes zero. Values of $0.50 \leqslant \mathrm{EF} \leqslant 1.00$ are considered acceptable (Singh, 2011). In this study, the values of EF vary from 0.74 to 1.00 during the calibration (Table 2) and 0.76–0.95 during the validation (Table 3), showing a good agreement between the predicted and observed groundwater levels.

3.2. Results of sensitivity analysis

The results of the sensitivity analysis of the model parameters are depicted in Fig. 6. It is obvious from the figure that hydraulic conductivity has a major impact on groundwater levels. An increase in hydraulic conductivity values results in deeper groundwater levels and vice versa. The specific yield of the aquifer is less sensitive as compared to K. Likewise, K values, an increase in S_y values results in deeper groundwater levels. The value of S_y given for one internal node has a little affect on the groundwater levels of the other internal nodes in the vicinity. The trend of the sensitivity analysis was almost same for all the nodes.

3.3. Simulating water management strategies

After the successful calibration and validation of the model, it was used to predict the future groundwater behaviour under various management options for the next 10 years. In a predictive simulation, the parameters optimized during calibration are used to predict the system response to future events. This phase of the modelling study will help to develop several water management scenarios to understand the basic features of the problems as well as to devise strategies to mitigate the problems of soil salinity and waterlogging, because each part of the study area is experiencing rising watertable. In the prediction mode, SGMP requires initial watertable elevations for the first year as well as the watertable elevation and the net recharge data (Q) of the internal nodes for the next two seasons. Based on such inputs, the model predicts the groundwater elevation of the internal nodes. In the present study, the watertable elevation data as observed in June 2009 are given as initial watertable elevations. Watertable elevations and net recharge for the October 2009 and June 2010 were considered as Q_1 and Q_2 for the next two seasons.

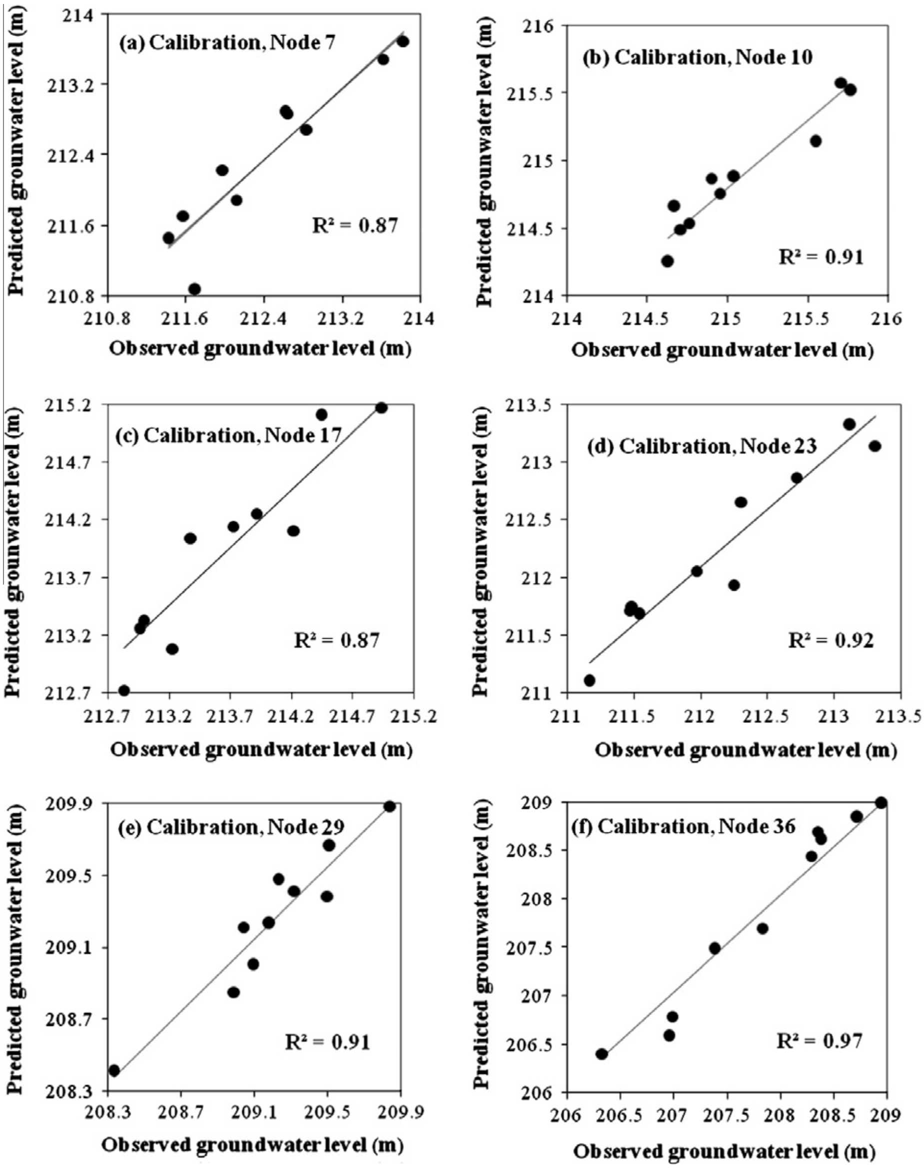

Fig. 4. (a–f) Comparison between observed and predicted groundwater levels during calibration for the nodes 7, 10, 17, 23, 29, and, 36.

Different scenarios considered for the present study assume several combinations of net recharge for the monsoon (Q_1) and winter (Q_2) season. Various water management options, simulated under different combinations of net recharges are given as follows:

Scenario 1: for both the seasons, net recharge data for season I and season II for the period 1997–2010 (calibration and validation phase) are averaged and taken as Q_1 and Q_2. This scenario would reveal the average conditions of the watertable in case present trend of recharge/discharge in the area do not vary much.

Scenario 2: actual recharge data for both the seasons of the year 1999–2000 are taken as Q_1 and Q_2. It can be noted that the year 1999 was a dry year with annual rainfall of 243 mm, compared to an average value of 566 mm. This scenario reveals that if few dry years occur in succession, what is likely to happen to the groundwater table.

Scenario 3: net recharge data for both the seasons of the year 1995–96 are taken as Q_1 and Q_2, which also represent the net recharge under, above-average rainfall condition (wet year), as that year had 1001 mm rainfall.

Scenario 4: average net recharge data as obtained for scenario 1 is decreased for both the seasons and taken as Q_1 and Q_2 for seasons I and II. This can be achieved by increasing discharge and/or decreasing recharge to the groundwater. This strategy might help to tackle the problem of rising watertable in the study area.

Scenario 5: several trials and errors were made in this combination, so that the watertable is stabilized at a safe depth ($\geqslant$3.0 m) during the simulation period. For this scenario, watertable was fixed at 3.0 m below ground level.

To avoid repetition and for the sake of brevity, results in respect of all the selected scenarios for the arbitrarily chosen nodes 10 and 36 are presented in Table 4 and described below.

3.3.1. Scenario 1: average condition

The results obtained for this scenario in the case of node 10 show an almost constant groundwater level, although a small rise of 0.13 m could be noticed during the simulation period of 10 years (Table 4). It can be concluded that if the average condition continues for the next 10 years as can be anticipated in normal circumstances, there might not be any significant fall or rise in the

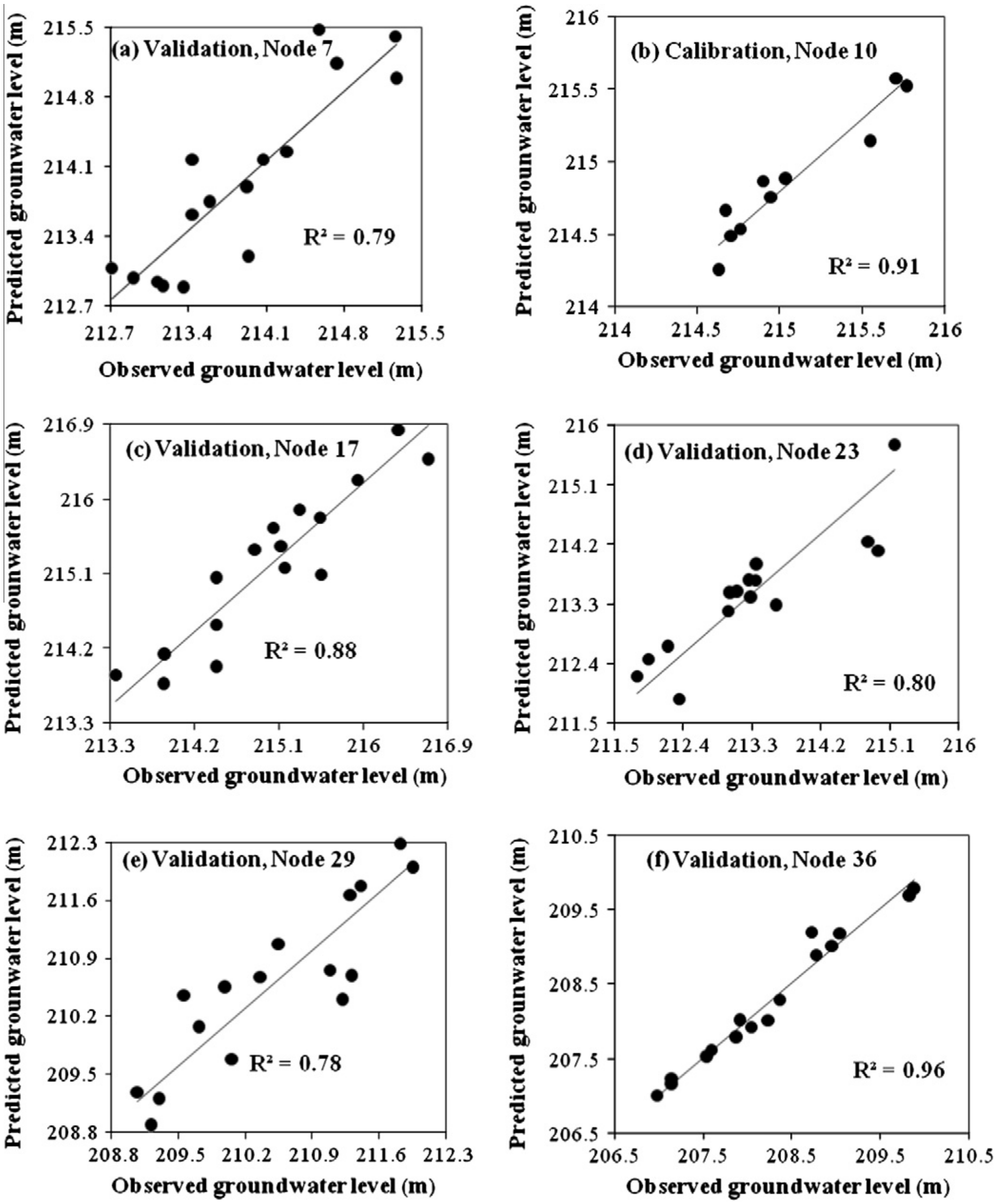

Fig. 5. (a–f) Comparison between observed and predicted groundwater levels during validation for the nodes 7, 10, 17, 23, 29, and, 36.

Table 2
Results of model calibration.

Calibration period (October 1997–June 2002)									
Node No.	R^2	ME	RMSE	EF	Node No.	R^2	ME	RMSE	EF
6	0.80	0.00	0.24	0.79	24	0.92	−0.17	0.30	0.99
7	0.87	0.06	0.43	0.97	25	0.91	0.01	0.21	1.00
10	0.91	0.20	0.32	0.93	28	0.88	−0.05	0.23	1.00
11	0.88	−0.25	0.46	0.85	29	0.91	0.05	0.18	1.00
12	0.94	0.09	0.27	0.93	30	0.91	0.02	0.17	1.00
16	0.79	−0.25	0.57	0.85	31	0.77	0.40	0.67	0.99
17	0.87	0.26	0.52	0.74	34	0.92	0.16	0.35	0.99
18	0.80	−0.12	0.42	0.95	35	0.94	0.02	0.34	1.00
19	0.84	−0.12	0.40	0.97	36	0.97	0.03	0.28	1.00
22	0.85	0.04	0.18	1.00	37	0.93	0.00	0.30	1.00
23	0.92	−0.08	0.29	1.00					

watertable. It may be noted that watertable in this case would remain between 2.32 and 2.94 m below the ground surface, during the simulation period. For node 36, an average rise of 0.05 m per year is expected such that the watertable elevation would be 207.48 m at the end of the simulation period. Although, watertable in node 36 is still at a safe depth at the end of the simulation period, rising watertable trend is alarming and needs immediate intervention. Groundwater levels in other nodes would vary between

Table 3
Results of model validation.

Validation period (October 2002–June 2010)									
Node No.	R^2	ME	RMSE	EF	Node No.	R^2	ME	RMSE	EF
6	0.92	−0.10	0.35	0.76	24	0.85	−0.13	0.43	0.83
7	0.79	−0.06	0.41	0.76	25	0.90	−0.25	0.43	0.85
10	0.91	0.08	0.42	0.78	28	0.77	0.15	0.54	0.82
11	0.81	0.07	0.45	0.77	29	0.78	0.10	0.47	0.78
12	0.75	−0.27	0.44	0.77	30	0.88	0.23	0.53	0.76
16	0.98	0.25	0.55	0.75	31	0.64	0.15	0.55	0.78
17	0.88	−0.20	0.40	0.81	34	0.76	0.10	0.53	0.77
18	0.73	0.27	0.55	0.88	35	0.84	−0.02	0.37	0.79
19	0.74	0.14	0.61	0.74	36	0.96	0.11	0.44	0.79
22	0.86	0.35	0.58	0.76	37	0.97	0.21	0.52	0.83
23	0.80	−0.15	0.47	0.80					

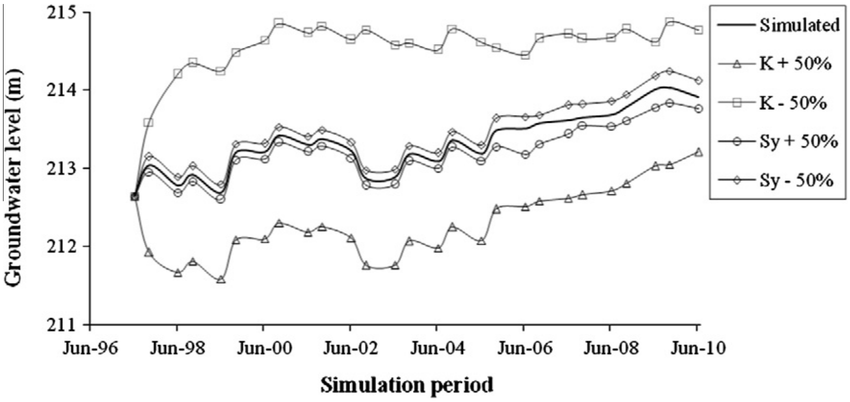

Fig. 6. Results of sensitivity analysis.

Table 4
Results of different water management scenarios.

Timestep	Groundwater level under different scenarios (m)									
	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
	Node 10	Node 36	Node 10	Node 36	Node 10	Node 36	Node 10	Node 36	Node 10	Node 36
0	215.29	206.98	215.29	206.98	215.29	206.98	215.29	206.98	215.29	206.98
1	215.90	207.72	215.55	207.68	216.23	207.72	215.55	207.63	215.55	207.49
2	215.30	207.04	214.96	206.93	215.52	207.23	214.97	206.88	215.30	206.97
3	215.91	207.81	215.44	207.67	216.49	207.97	215.45	207.61	215.55	207.50
4	215.31	207.06	214.87	206.89	215.72	207.45	214.87	206.84	215.29	206.97
5	215.91	207.82	215.36	207.61	216.67	208.21	215.36	207.55	215.55	207.50
6	215.32	207.14	214.81	206.83	215.95	207.65	214.82	206.74	215.30	206.97
7	215.92	207.86	215.31	207.58	216.84	208.43	215.32	207.53	215.56	207.51
8	215.33	207.18	214.77	206.74	216.22	207.85	214.77	206.71	215.34	206.98
9	215.92	207.92	215.28	207.56	217.09	208.61	215.27	207.51	215.55	207.51
10	215.35	207.23	214.74	206.72	216.39	208.03	214.73	206.65	215.34	206.98
11	215.93	207.97	215.25	207.51	217.32	208.78	215.25	207.45	215.56	207.51
12	215.37	207.27	214.72	206.66	216.54	208.19	214.73	206.62	215.34	206.98
13	215.93	208.01	215.24	207.51	217.38	208.92	215.25	207.46	215.56	207.51
14	215.38	207.33	214.71	206.59	216.65	208.32	214.72	206.54	215.34	206.98
15	215.93	208.07	215.23	207.44	217.55	209.03	215.23	207.39	215.56	207.51
16	215.40	207.34	214.70	206.52	216.81	208.43	214.71	206.51	215.34	206.98
17	215.94	208.14	215.22	207.39	217.67	209.13	215.23	207.34	215.56	207.51
18	215.41	207.45	214.69	206.49	216.98	208.51	214.70	206.48	215.34	206.99
19	215.95	208.18	215.22	207.35	217.85	209.19	215.22	207.31	215.56	207.51
20	215.42	207.48	214.69	206.45	217.09	208.58	214.70	206.48	215.34	206.99

2.64 and 3.58 m below ground surface during the simulation period under this scenario.

3.3.2. Scenario 2: dry condition

Rainfall conditions in the region are quite variable both, temporally and spatially, many times a few years of continuous drought can be expected (Singh, 2012e). The result for node 10 is shown in Table 4, as expected, watertable is declining at an average rate of 0.06 m per year during the simulation period, which is obvious because of low net recharges during the drought years. The depth to watertable would remain within a range of 2.68–3.55 m. For node 36, the rate of watertable decline is almost same as that of node 10. During the simulation, an average decline in watertable is estimated to be 0.053 m per year. This indicates the condition of over-exploitation and would require some restrictions on the use of groundwater. Declining watertable during this scenario would be noticed for other nodes as well.

3.3.3. Scenario 3: wet condition

This scenario reveals that if few wet years occur in succession, what is likely to happen to the groundwater level. Watertable simulated for node 10 shows a rising trend, starting from a depth of 2.95 m, in the beginning of the simulation, watertable rises at an average rate of 0.18 m per year to reach at 1.15 m, at the end of the simulation period, however the rate of rise was higher in the initial years. Similar to node 10, excess rainfall condition would generate same rising watertable trend for the node 36. Watertable in this node rises at an average annual rate of 0.16 m to register a total rise of 1.60 m during the simulation period. Similar rising watertable trend would be noticed for all the internal nodes during this scenario. In this scenario, soil salinity build-up can be expected in the root zone by capillary rise. Increased exploitation of groundwater resources must be made popular among the farmers to stop the watertable rise.

3.3.4. Scenario 4: reduced net recharge condition

The rising watertable in the study area can be mitigated either by increasing tubewell discharge or by decreasing net groundwater recharge; in this scenario the average net recharge in both the seasons was reduced to study the behaviour of watertable after 10 years. The simulation results obtained for the node 10 show a declining watertable trend. Watertable in this case would fall at a rate of 0.059 m per year. This will result in a watertable depth of 3.54 m at the end of the simulation period; this would be the start of the reversal of the present rising trend. This is not a serious condition from over-exploitation point of view but little improvement in the cropping pattern would be required to prevent that situation. Watertable shows a declining trend for the node 36 as well, although at a slower rate of 0.05 m per year. Other nodes would also experience a watertable decline under this scenario.

3.3.5. Scenario 5: maintain watertable at a safe depth

The ultimate aim of any water management project is to maintain the watertable at a depth, which is neither too shallow nor too deep. It helps to avoid the adverse effects of waterlogging and at the same time would not lead to over exploitation. Thus, in this scenario, trial and error was used to find out average net recharge/discharge that would stabilize the watertable at a predecided depth. For node 10, it was proposed to achieve a watertable depth of about 3.0 m during monsoon season. The net recharge for the monsoon season has been decreased by 5% of the average value, while no change in net recharge has been made for the winter season. This scenario will result in the watertable to decline from a level of 2.95 m in the beginning to 2.98 m in the third year of the simulation, after that watertable would remain at a depth level of 2.9 m throughout the simulation period. For the node 36, a decrease of 20% in net recharge value for monsoon season and no change in net recharge for winter season has generated good result. The watertable in this case would stabilize from the beginning throughout the simulation period. This situation is also very reasonable for this part of the study area. Other nodes would need a decrement between 3% and 19% in net recharge value of monsoon season to achieve a safe watertable depth.

3.4. Impact of potential policy changes

The tested model was used as a tool to evaluate the impact of various policy changes on the groundwater behaviour of the study area. The following practical/feasible water management interventions were identified for studying and assessing their impact on watertable behaviour: (1) increased tubewell draft; (2) change in cropping pattern with reduced rice area; (3) canal lining; (4) change in water pricing policy from the existing *warabandi* to a warimetric system; and (5) water supply according to demand rather than based on cultivable area. The impact of various policy changes are compared with the reference condition (existing condition) and reported in Fig. 7. This can be seen that the average groundwater level in the area would fall under each intervention, though; the rate of fall would differ from one intervention to other.

4. Conclusions and recommendations

Based upon the simulation results, it is apparent that SGMP model seems to be an effective tool for groundwater simulation,

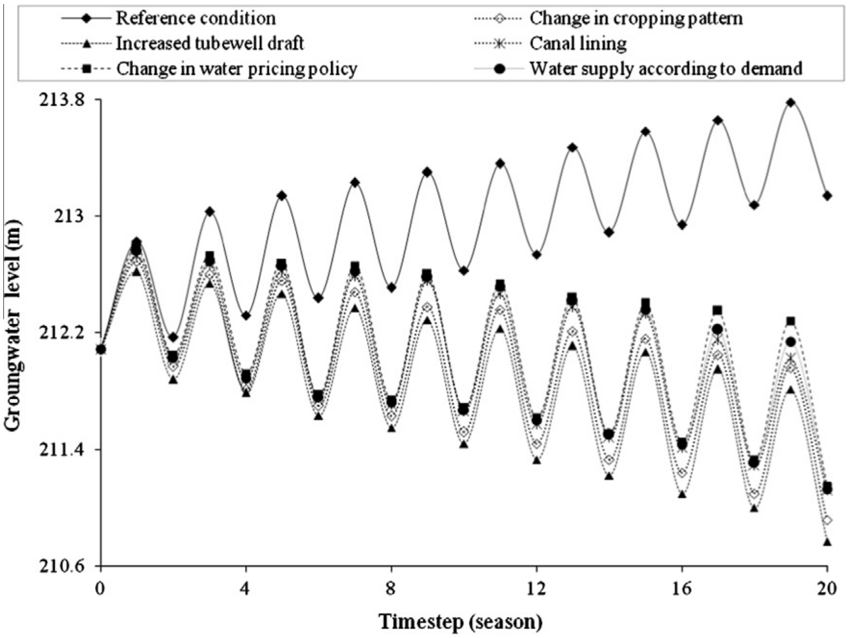

Fig. 7. Impact of potential policy changes on groundwater level in the study area.

as evident from the error analysis. It has the potential of assessing the watertable behaviour due to various interventions. The results of simulation studies of existing and proposed water management policy, therefore, may form the basis for the identification of appropriate water management plans for the future. The following specific conclusions and recommendations could be made from the present study:

- Groundwater abstraction should be increased by installing more tubewells at new locations and encouraging farmers to use groundwater in conjunction with good quality canal water.
- Cropping pattern should be changed and salt tolerant varieties of crops should be introduced in place of rice crop, as salt tolerant crops may be irrigated with poor quality groundwater thereby avoiding the undesirable effects of saline water on salt sensitive crops.
- Water distribution, management, and pricing policies should be reconsidered. At present, canal water release pattern is governed by cultivable area rather than on water requirements of irrigated crops. Distribution of canal water based on spatially distributed crop water requirements could result in significant saving in groundwater recharge due to reduction in water losses in conveyance system.
- Though it is capital intensive task, lining of surface irrigation system could also be suggested as the seepage rate from a lined canal is about one-fourth than that of an unlined canal.

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