Groundwater assessment in a canal command area for sustainable irrigation in a part of the Indo-Gangetic alluvial plain

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The growing dependence of irrigation on groundwater and its excessive use for other purposes has an adverse impact on the resource domain. This has resulted in unsustainable over-extraction and subsequent lowering of the groundwater table. The present study shows that groundwater levels can be kept near stable even with more extraction for increased cropping intensity of up to 222% by opting conjunctive use, as against the present intensity of 163.1%. In addition, the groundwater sustainable area increased from 65% to 92% and the groundwater depletion area decreased from 30% to 7%. The waterlogged area also reduced from 5% to 1% in a period of three years, thereby increasing gross margins. Groundwater system simulation shows that groundwater level will remain sustainable even after 10 years at 222% cropping intensity by adopting conjunctive use of groundwater with canal water.

Keywords: Conjunctive use, cropping intensity, groundwater assessment, irrigation.

GLOBALLY, urban settlements are facing depletion of water resources due to increasing water demands for the population and industries[1–4]. Irrigation sector has been under pressure to produce more with lower supplies of water[5,6]. The growing demand for water to meet urban and industrial needs has raised serious concerns regarding the future of irrigated agriculture in many parts of the world[7]. In large canal command, integrated management of surface and groundwater resources can improve water-use efficiency and agricultural productivity[8,9]. Water supply may cross local, state and even international boundaries. Hence, a wider (basin-wise) comprehensive perspective is imperative for long-term planning process[10]. Local-scale groundwater flow model was developed by Ebraheem *et al.*[11], and Palma and Bentley[12] for management of groundwater resources. Abdulla *et al.*[13] performed groundwater system modelling of Azraq basin in Jordan.

The inefficient water distribution networks, growing urban population and industries have accelerated the water demand in the vast Indo-Gangetic Plain. A large number of licenced and unlicensed tube wells have been installed resulting in lowering of groundwater levels. Therefore, proper groundwater system modelling and management is imperative. Groundwater flow modelling of Hindon–Yamuna interfluve region, western Uttar Pradesh (UP), India was done by Alam and Umar[14]. Gosh and Kashyap[15] utilized optimization technique in pre-calibrated simulation model of groundwater flow. Singh *et al.*[16] optimized sustainable groundwater extraction management of Lucknow city.

In view of the impending threats to water from both surface and groundwater sources, it has become imperative for imposing integrated water resources management[17,18]. In the present study, groundwater system modelling has been performed on integrated framework. First, groundwater system is simulated under existing irrigation practices. The calibrated and validated model is further utilized to simulate groundwater stresses (recharge/discharge) under improved cropping intensity vis-à-vis uses of groundwater and surface water (canal water).

Study area

Uttar Pradesh comprises 240,928 sq. km of Gangetic Alluvial Plain in India. The state lies between 23052′12″–30024′30″N and 77005′38″–84038′30″E. UP can be broadly divided into two physiographic units – the Ganga Plain, and the Bundelkhand and Vindhyan Plateau. The former covering 85% of the state, is a vast, flat expanse of alluvium having a gentle southeasterly regional slope. The highest elevation is around 350 m amsl in the northwestern parts and lowest is 60 m amsl in the extreme southeastern part of UP. The Ganga Plain has three sub

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divisions – the Terai in the northwest, the Central Ganga Plain in the middle and the marginal alluvial plain in the south. The master drainage of the state is the River Ganga and its tributaries. The Ramganga, Gomti and Ghagra are the main left-bank tributaries, while Yamuna is main right-bank tributary. All these rivers, except Gomti, originate from the Himalayan ranges and are snow-fed. Initially, the rivers flow southwards in the northwestern part of the state, then turn southeastwards and finally leave the state in an easterly direction.

UP experiences sub-tropical climate. The rainy season confined between June and September contributes 80–85% of the annual rainfall. Annual rainfall over the state ranges between 800 and over 1400 mm. A large part of the state is underlain by fluvial sediments laid down in the foredeep between the Plateau region in south and the Himalaya in north during the Quaternary by the Indus–Ganga system of drainage over the Precambrian topography. UP consists of 75 districts and 820 blocks. Groundwater is under stress as it contributes to about 71% of the irrigation needs of the state.

Groundwater exploration

In the Indo-Gangetic Plain of UP sediments are generally coarser in the north and gradually become finer southeastward. This zone mainly consists of two parts – the Terai and the Alluvial Plain. The unconsolidated zone is porous and permeable with primary intergranular porosity and has good groundwater potential.

Four aquifers have been identified in the Central Ganga Plain on the basis of lithology and interpretation of electrical logs of boreholes drilled which are expressed in terms of bgl (below ground level) – first aquifer (0.0–150.00 m bgl); second aquifer (160.00–210.00 m bgl); third aquifer (250.00–360.00 m bgl) and fourth deep aquifer (380.00–600.00 m bgl). The first aquifer group, which is under unconfined to semi-confined conditions, is the most potential aquifer. It is being extensively exploited through private as well as Government tube wells to meet the drinking water and irrigation needs.

Groundwater regime monitoring

The water-level monitoring at more than 1200 hydrograph stations of the Central Ground Water Board (CGWB) and State Ground Water Department, UP, spread across all the blocks of the state was carried out four and six times respectively in a year. The groundwater levels in the state are as low as 1 and as high as 35 m bgl. In Bhabar areas, the depth to water level varies from 8 to more than 35 m bgl, whereas in Terai area it ranges from less than 1 to 10 m bgl. The central and eastern parts of the state show a wider range of water levels varying from less than 1 m bgl (canal command area) to more than 30 m bgl along the natural levees formed on either side of River Ganga. Major part of western UP is characterized by deep water levels. These water levels have shown significant declining trend over the last two decades in some parts of the state due to over-exploitation of groundwater resource.

The main factor contributing to the depletion of groundwater is its over-exploitation to meet the demands of various sectors. The declining trend is adversely affecting water supply, electricity consumption, agricultural production and economy of the state.

Groundwater system simulation model

A groundwater model, Visual MODFLOW is represented by the following three-dimensional groundwater flow equation (McDonald and Harbaug)

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+w=S_s\frac{\partial h}{\partial t}, \tag{1}$$

where K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y and z axes respectively (L/T); h is the hydraulic head (L); W the volumetric flux per unit volume representing either sources and/or sinks of water: $W < 0$ for flow out of the groundwater system, and $W > 0$ for flow in (T^{-1}); S_s is the specific storage of the porous material (L^{-1}) and t is the time (T).

Rainfall, evapotranspiration and surface run-off are hydrological inputs which determine the recharge. Groundwater table, artesian pressures (confined aquifer), and hydraulic head along the boundaries of the model on the one hand (the head conditions), to groundwater inflows and outflows along the boundaries of the model on the other (the flow conditions) were considered as boundary conditions.

Groundwater system simulation for the study area

Model set-up

River Gomti and Balrampur drain doab having an area of 66,939 ha, lie between 25050′–26010′N and 82000′–82040′E, in nine blocks of Sutanpur, Pratapgarh and Jaunpur districts, UP have been taken as the model study area (Figure 1). Ramganj distributary system having canal command area of 39,861 ha supplies water through a canal network of 243 km using 35 minors/distributaries for irrigating mainly rice and wheat cycle.

Although the alluvial sequence of the study area is spread up to 400 m, modelling has been performed for the upper unconfined layer. The X-axis of the developed modelling framework in MODFLOW lies between

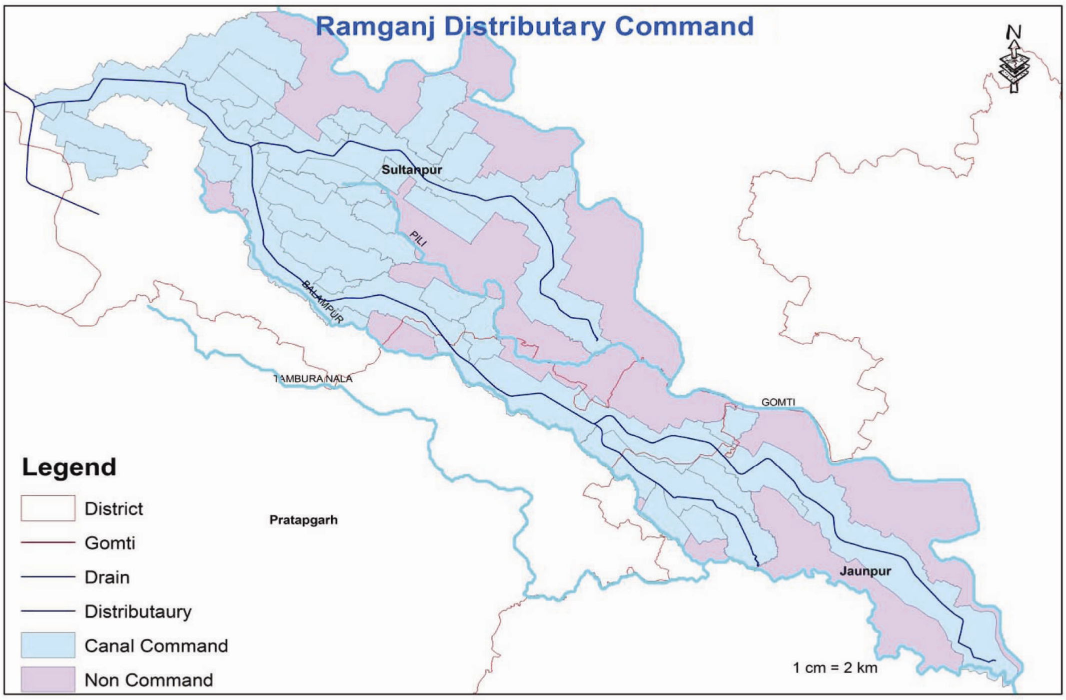

Figure 1. Details of command area covered by Ramganj distributary system.

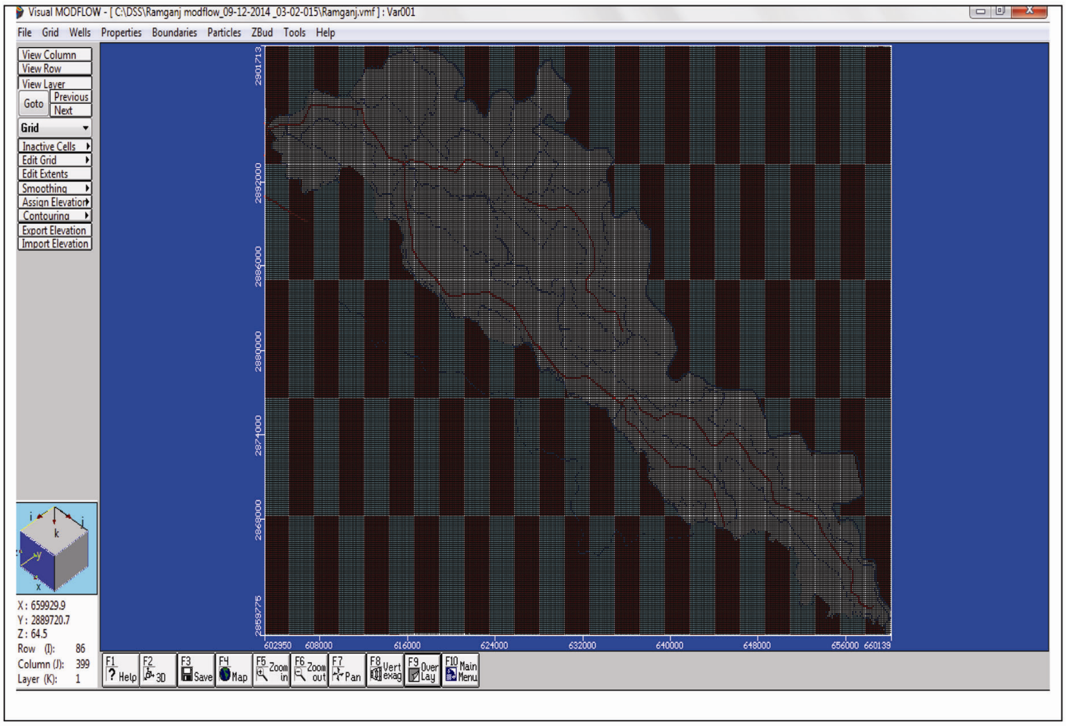

Figure 2. Model developed for the study area.

602,950 and 660,139 m, while the *Y*-axis lies between 2859,775 and 2901,713 m. The modelling framework area is 234,859 ha or 2348.59 sq. km (56.836 km × 41.324 km) (Figure 2). Model area of 57.189 km × 41.938 km has been divided in 400 columns and 300 rows in a grid size of 143 m × 140 m.

The topography of the model area based on Shuttle Radar Topographic Mission (SRTM) 90 M resolution

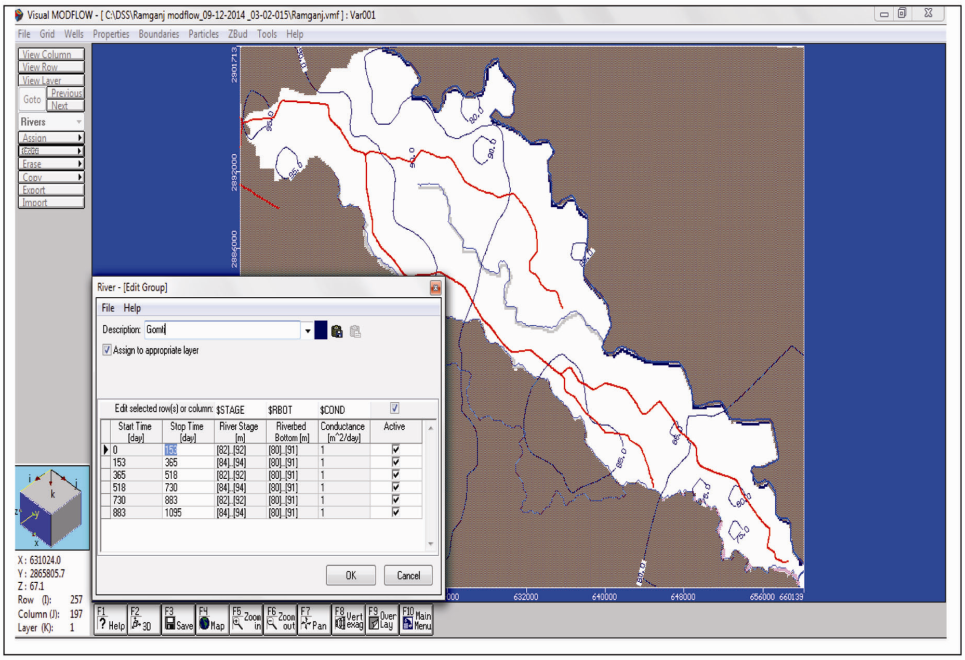

Figure 3. River boundary conditions.

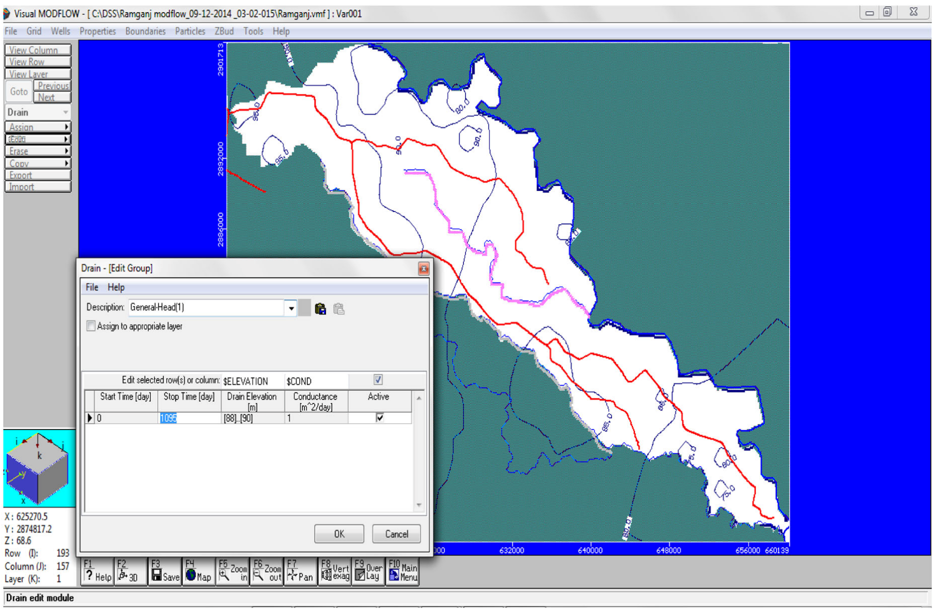

Figure 4. Status of drains in the study area.

data predicts that the water levels in the area vary from 68 to 110 m in decreasing order from west to east as well as from north to south. A single-layer unconfined aquifer model at an average depth of 50 m is developed. On the basis of available reports and strata charts, a reasonable value of hydraulic conductivity of 1.5 m/day was considered.

The average value of specific yield was taken 0.15 according to the recommendation of CGWB for various grain-sized alluvial materials in the 1997 groundwater Estimation Committee norms. For sensitivity testing, values of 0.10 and 0.20 were used to represent the grain size range most commonly observed in the state tube-well logs. In the CGWB report of 1996, the upper aquifer in Jaunpur, Sultanpur and Pratapgarh districts of the study area showed an average 50 m thickness. Alluvium in the area consisted of multiple inter-fingering layers of sand, silt and clay that are semi-continuous in the study area. There was also a layer of clay about 20–30 m thick.

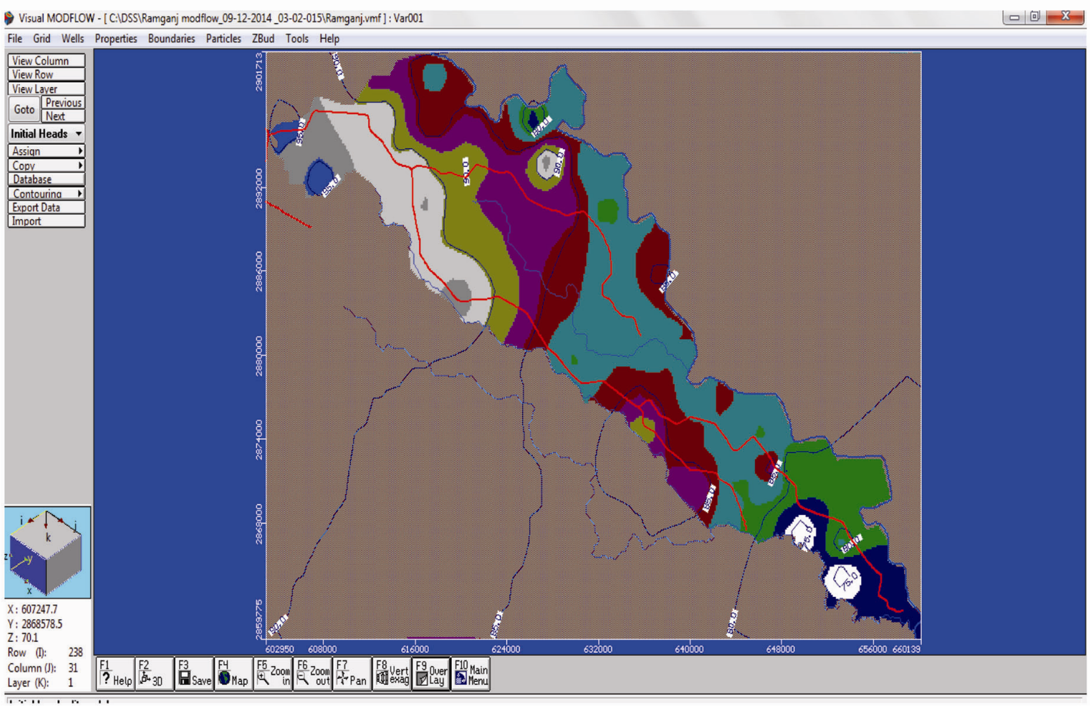

Figure 5. Initial groundwater levels.

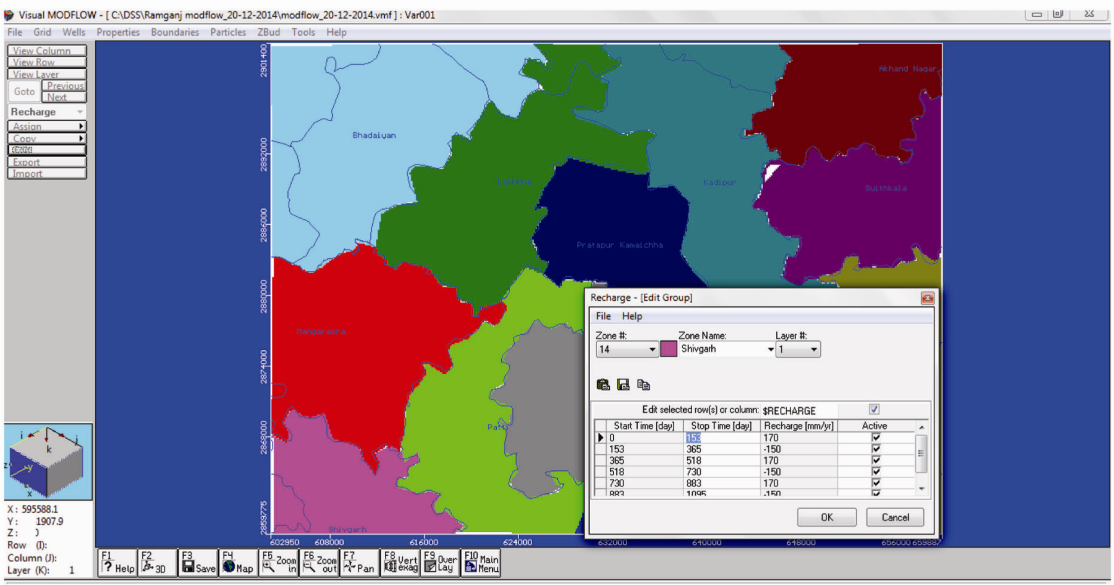

Figure 6. Recharge zones at block level in the groundwater model.

Seasonal inputs for the monsoon and non-monsoon periods have been used in the model runs. Three-year time-period from 15 June 2011 to 14 June 2014 was utilized to compare predicted and observed groundwater levels. Boundary conditions of a groundwater model are vital for conceptualizing the same. On the northern side of River Gomti and southern side of River Balrampur, the catchment divides were taken at the sub-basin boundaries with 'no-flow' conditions. At the confluence, the two boundaries meet on the southeastern side. River package in Visual MODFLOW was used to characterize the two rivers. The landmark bed elevations were used to define the bed of the river through linear interpolation. Figure 3 shows the river boundary conditions.

The depth of water in the rivers was averaged to 4 m for the monsoon period of 153 days starting from 15 June to 15 October and 2 m for non-monsoon period from 16 October to 14 June for River Gomti. Similarly, for River

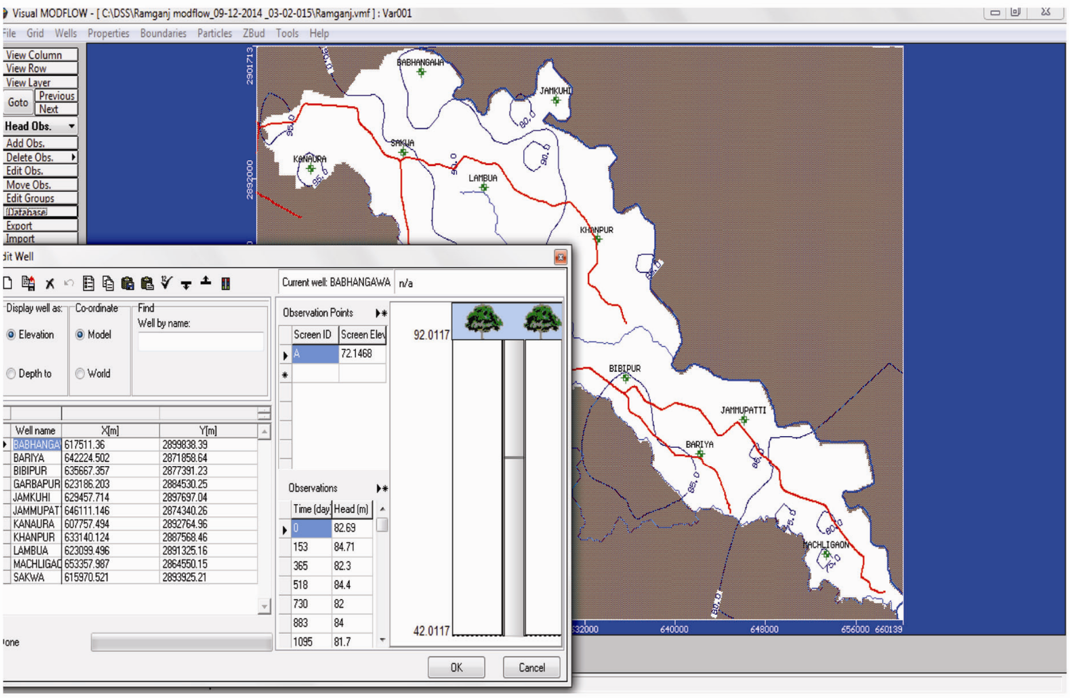

Figure 7. Monitoring wells used for water-level calibration.

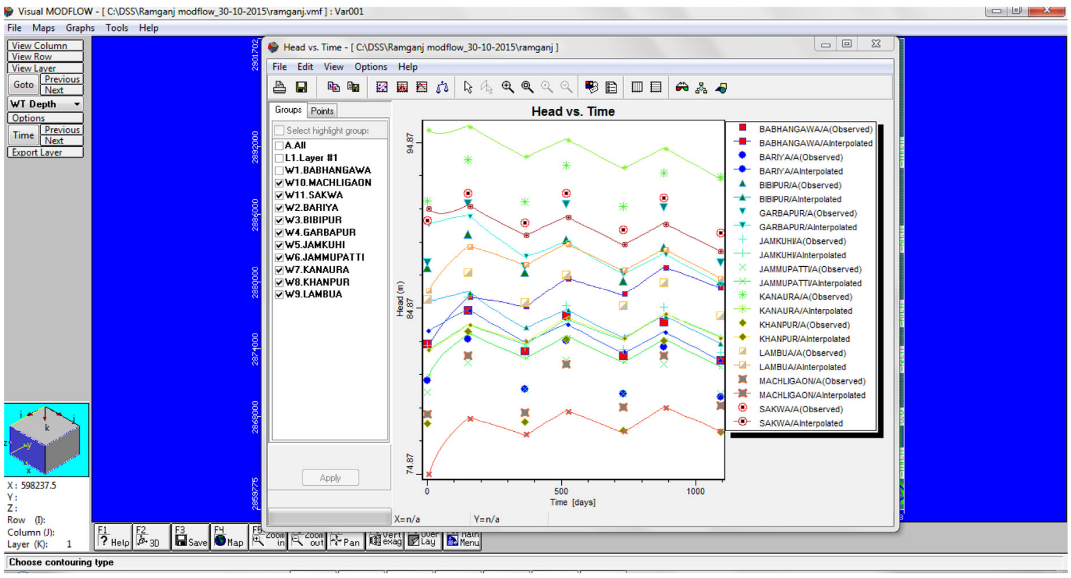

Figure 8. Model calibration run showing the calibrated and actual water levels.

Balrampur on the other side, an average depth of 3 m for the monsoon period and 1.5 m for the non-monsoon period has been considered. The bed layer (M) was assumed as 0.5 m thick having vertical hydraulic conductivity (K) of 1.5 m/day. Hydraulic conductance (C) was calculated within the model as

$$C = \frac{K \times L \times W}{M},$$

where L is the length of the river in each cell (m).

Pili drain lying between the Gomti and Balrampur rivers is also being used for surplus run-off in the command distributaries. Since the flow data for different periods of the drain are not available, an average depth of flow for the entire period has been assumed depending on field enquiry (Figure 4). Initial groundwater levels of 60 monitoring wells of the study area were collected for pre-monsoon date of 15 June 2011 from automatic groundwater-level recorders. Figure 5 shows the initial water-level contours generated from available data of imported files

Table 1. Details of present cropping pattern in Ramganj distributary command area of 39,861 ha according to National Informatics Centre Statistics 2011–12

	Crop	Crop area (ha)	Area (%)	Seasonal crop as percentage of polygon area	Seasonal crop as percentage of net sown area
Kharif	RICE_K	12,585.24	32	47	72.3
	MAIZE_K	3,456.411	9		
	Other_Kharif	2,830.845	7		
	Kharif_Fallow	14,200.55	36	36	
Rabi	WHEAT	16,953.69	43	58	89.2
	GRAM	2,891.17	7		
	Other_Rabi	3,143.944	8		
	Rabi_Fallow	10,084.24	25	25	
Zaid	URD_J	11.85427	0	1	1.6
	Other_Jaayad	212.8793	1		
	Jaayad_Fallow	32,848.32	82		
Perennial	SUGARCANE	91.44553	0		
	Vegetation	1,357.628	3	16	
	Wasteland	5,338.749	13		
Net sown area				65	
Cropping Intensity as percentage of polygon area	106				
Cropping Intensity as percentage of net sown area					163.1

of 60 observatory wells on GIS platform. Net recharge values for the model area have been calculated at block level, based on the Groundwater Estimation Committee Report of 1997. Groundwater extraction from private bore wells has been calculated separately based on available borings and average running hours for each of the *rabi* and *kharif* periods (Figure 6). Groundwater levels for 11 monitoring wells, for which data for the three complete years are available, have been used for comparison with the model run results (Figure 7).

Results and discussion

Model run for calibration

The developed model was run for three years starting from 15 June 2011. The thickness of the upper unconfined layer was taken as 50 M for modelling purposes based on bore-well logs, as groundwater extraction is mainly limited to the upper strata in shallow bore wells for irrigation purposes. The different aquifer parameters such as specific yield (0.15%) and hydraulic conductivity (15 m/day in *X*- and *Y*-directions and 1.5 m/day in the *Z*-direction) were taken based on bore-well logs and pump test results. The net recharge applied at block level was calculated outside the model domain based on the 1997 Groundwater Estimation Committee Report. The results show that for the net recharge values calculated at block level according to the Groundwater Estimation Committee norms (1997), with the current cropping intensity of 163.1% and prevailing irrigation practices, the model run output shows a correlation coefficient of 0.94–0.92 between the observed and predicted groundwater levels at different stages of the running period of three years. Table 1 provides details of existing cropping patterns for the study area, based on National Informatics Centre statistics. The present cropping intensity is 106% (47%K, 58%R and 1% Zaid) of polygon area or 163.1% (72.3%K, 89.2%R, 1.6% Zaid) of net sown area; the net sown area is only 65%.

Spatial variation in groundwater levels for the study area (Figure 8) predicts that with current irrigation practices for the cropping intensity of 163.1%, depletion of groundwater levels in the wells selected in non-command and tail canal command areas is between 0.5 and 1.0 m/yr. In the head canal commands, where the canal density is good, there is a rise in groundwater levels between 0.5 and 1.0 m/yr. Field visits also predict that the areas adjacent to canals, where canal water is easily accessible, experience waterlogging, and non-command and tail canal command areas face depletion in groundwater levels, thereby increasing the energy cost through diesel-driven private borings.

Sensitivity analysis

This was performed by varying model parameters over the potential range of values for the key parameters of hydraulic conductivity, specific yield and river leakage. The hydraulic conductivity values were not sensitive in the calculation of groundwater levels as they vary in a relatively small range for fine sand. A single value of 15 m/day for hydraulic conductivity was adopted. The specific yield varied between 0.10 and 0.20 in the short term. Specific yield affects fluctuations in groundwater levels between pre- and post-monsoon conditions. For a

Table 2. Status of district-wise groundwater resource potential (2004, 2008 and 2012) according to GEC-97 norms

	Net annual groundwater Recharge/potential (m)			Existing gross groundwater draft for all uses (m)			Stage of groundwater development (%)		
Assessment unit	2004	2008	2012	2004	2008	2012	2004	2008	2012
District Jaunpur	0.41	0.36	0.32	0.24	0.28	0.27	58.26	77.36	82.77
District Pratapgarh	0.24	0.21	0.35	0.08	0.13	0.24	33.53	60.56	69.86
District Sultanpur	0.41	0.38	0.35	0.19	0.28	0.24	46.09	72.77	69.94
Average	0.35	0.32	0.34	0.17	0.23	0.25	45.96	70.23	74.19

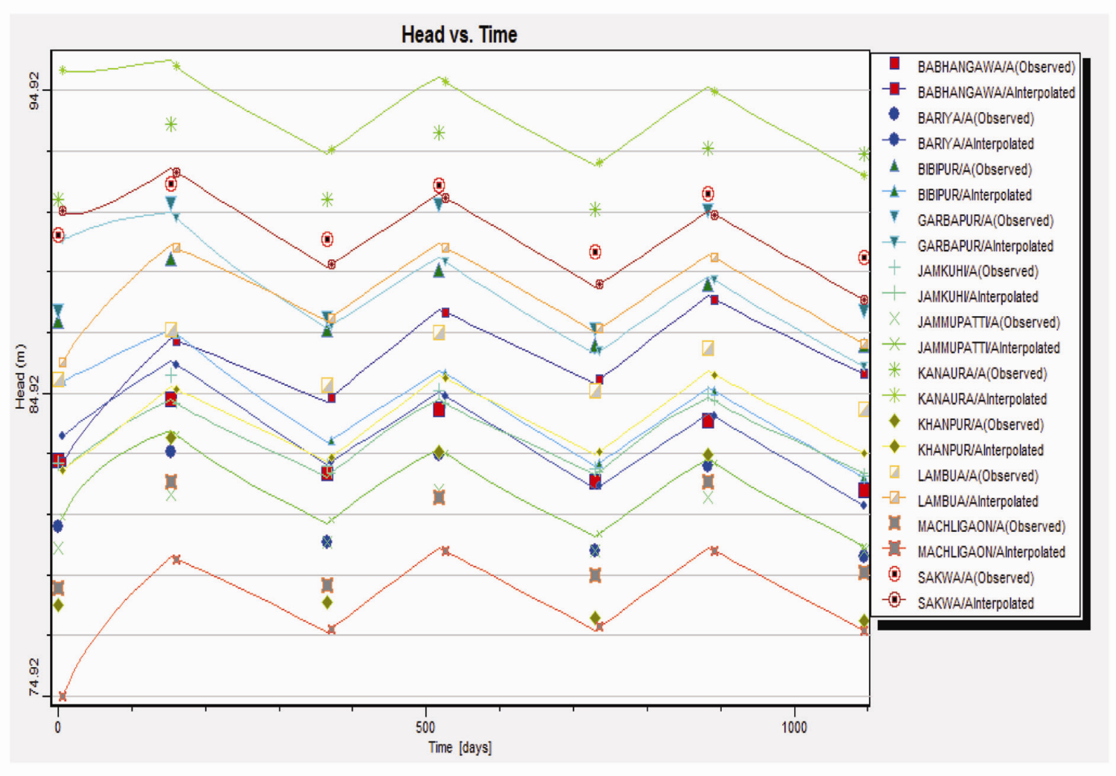

Figure 9. Groundwater levels for current cropping intensity of 163.1%.

net increase in recharge per year, the predicted groundwater levels showed an increasing trend in all the observatory well locations, while for a net decrease in recharge per year the predicted groundwater levels showed a decreasing trend in all the observatory well locations.

Model predictions

For future predictions in the model area, the cropped area and its crop water requirement have been calculated outside the model domain for different cropping intensities, and uniform net recharge values required were calculated, to see the impact of model run on groundwater levels if conjunctive use was employed. Groundwater assessment done for districts of the study area under Groundwater Estimation Committee 97(GEC-97) norms is shown in Table 2. It shows an annual recharge of 340 mm/yr from all sources, while the present annual draft is only 250 mm/yr for the current cropping intensity of 163.1%. Adopting conjunctive use with net uniform recharge value of 340 mm/yr on the whole area mainly in rainy season from 15 June to 15 October and groundwater draft of 250 mm/yr from 16 October to 14 June, showed a rising trend in groundwater levels at all locations as predicted in the model run (Figure 9).

Further, adopting conjunctive use for the proposed cropping intensity of 222% of net sown area by keeping the net recharge value of 340 mm/yr on the whole area mainly in the rainy season from 15 June to 15 October and groundwater draft of 340 mm/yr from 16 October to 14 June, simulation results showed that groundwater levels in pre- and post-monsoon periods remained sustainable. However, during non-monsoon period groundwater

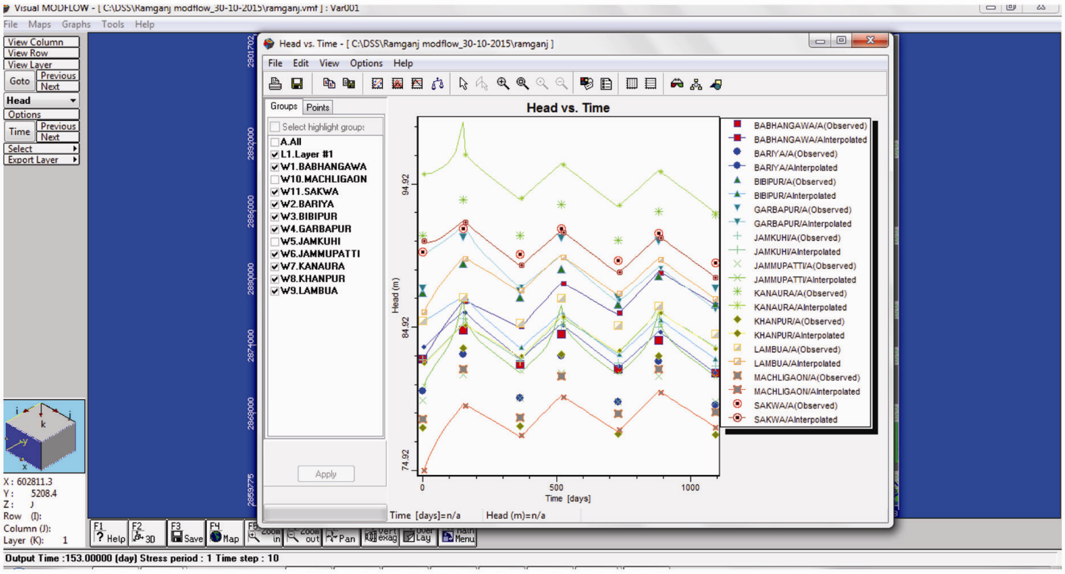

Figure 10. Groundwater levels for proposed cropping intensity of 222%.

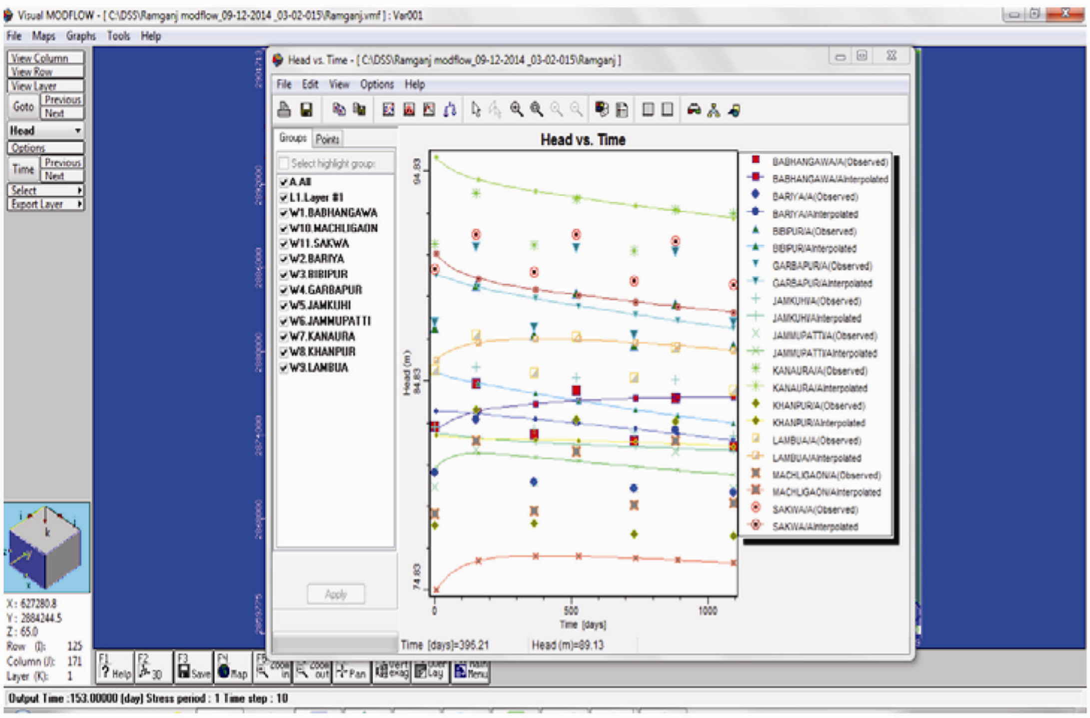

Figure 11. Groundwater levels at the predicted uniform net recharge of –90 mm/yr for the proposed cropping intensity of 280%.

levels showed a declining trend from post- to pre-monsoon period, and further it showed an increasing trend during the rainy season (Figure 10). Increasing the cropping intensity of 280% of net sown area by keeping uniform net recharge value of –90 mm/yr, simulation results showed that groundwater levels begin depleting at a much faster rate at all the locations (Figure 11).

Groundwater simulation model has been employed with conjunctive use for a period of three years: the groundwater sustainable area for the present cropping intensity of 163.1% of net sown area will increase to 92%, as against the sustainable area of only 65% for the present cropping intensity of 163.1% of net sown area under current irrigation practices. Further, the groundwater

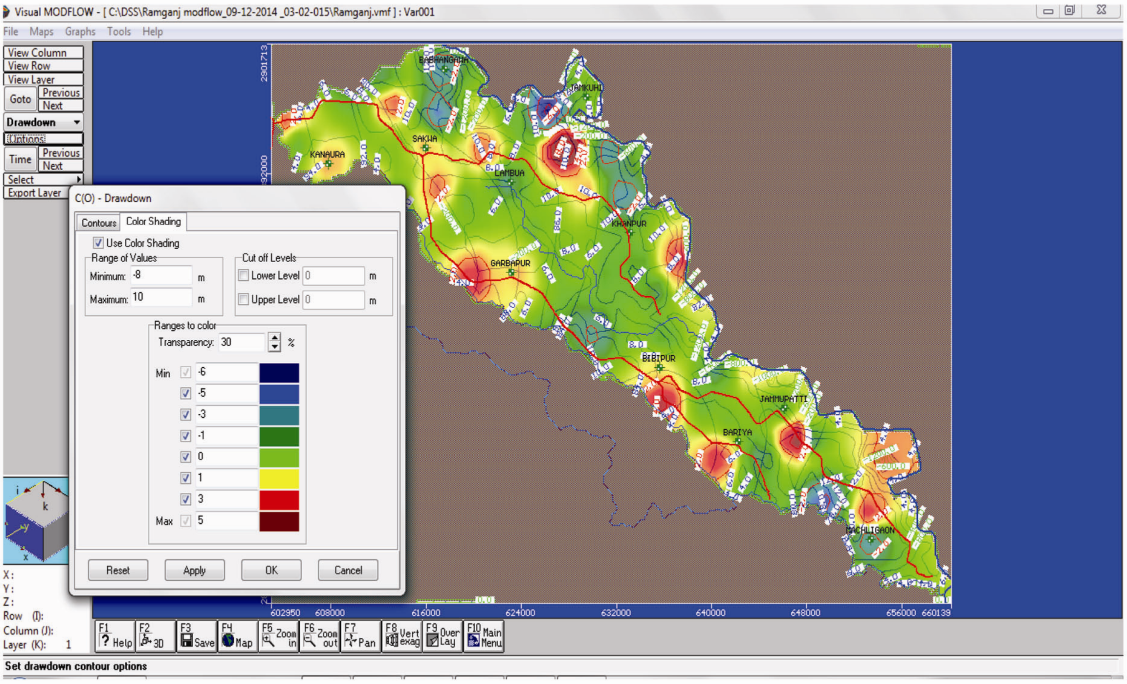

Figure 12. Draw-down in groundwater levels during a period of three years under current irrigation practices for the existing cropping intensity of 163.1%.

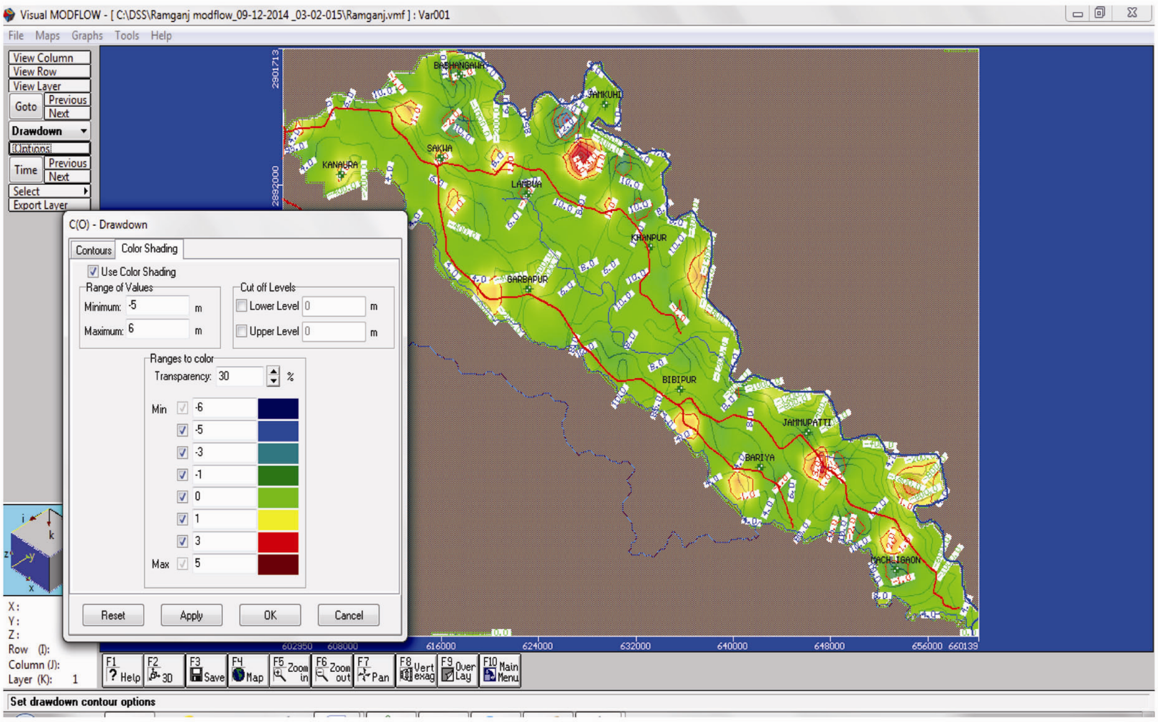

Figure 13. Draw-down in groundwater levels under the present cropping intensity of 163.1% during a period of three years, if conjunctive use is implied.

depletion area will reduce from 30% to 7%, having yearly depletion of more than 0.34 m and the waterlogged area will reduce from 5% to 1%, where the rise in groundwater levels is more than 0.34 m/yr (Figures 12 and 13).

Groundwater simulation model has been employed with conjunctive use implementation for a period of 10 years from June 2011 to June 2020. For the net recharge of 340 mm/yr, mainly in the rainy season from 15 June to

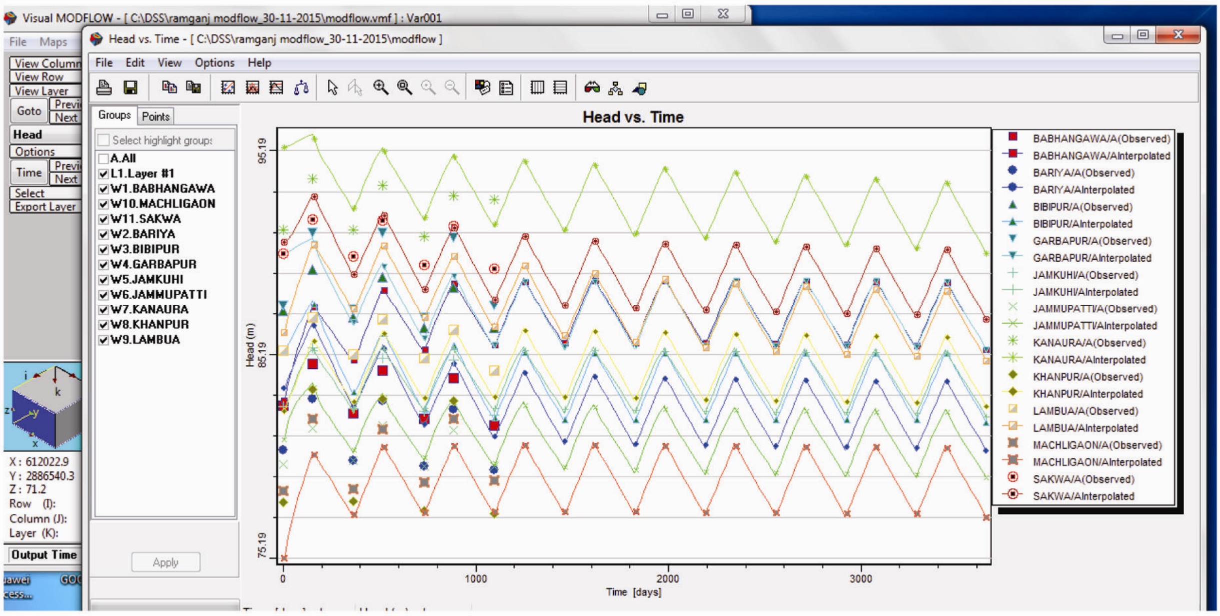

Figure 14. Groundwater behaviour under proposed cropping intensity of 222% for a period of 10 years, if Conjunctive use is implied.

15 October and groundwater draft of 340 mm/yr from 16 October to 14 June, the groundwater levels in pre- and post-monsoon periods remained more or less sustainable at 222% cropping intensity (Figure 14).

Conclusion

In this study, groundwater modelling framework for irrigation development by conjunctive utilization of canal water and groundwater is presented. Groundwater simulation and conjunctive use implementation have been demonstrated in Ramganj distributary canal system, part of the Indo-Gangetic Alluvial Plain in UP. Groundwater withdrawal required for increasing the maximum cropping intensity to 222% (from 163.1%) has been simulated by imposing total withdrawal of 340 mm/yr, as against the total recharge of 340 mm/yr (net annual recharge of 0 mm/yr) in the simulation model.

The sustainable area was 65% at 163.1% cropping intensity with current irrigation practices and it increased to 92% with the implementation of conjunctive use. Groundwater depletion area was 30% at 163.1% cropping intensity and it decreased to 7% with the implementation of conjunctive use. Groundwater withdrawal also marginally reduced in waterlogged areas from 5% to 1%.

Further, 10-year simulation shows that if conjunctive use is adopted, the groundwater levels in pre- and post-monsoon periods will remain sustainable even at 222% cropping intensity. However, cropping intensity can further be increased by choosing less water-consuming crops and opting for sprinkler and drip irrigation methods. Groundwater withdrawal may add to the cost of lifting groundwater through electric/diesel-driven private bore wells. However, there is a saving in terms of overall additional gain for bringing prevailing waterlogged and barren areas under cultivation, thereby increasing gross margin to farmers.

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Received 21 February 2016; accepted 30 August 2016

doi: 10.18520/cs/v112/i03/478-489