Groundwater System Simulation and Management Using Visual MODFLOW and Arc-SWAT

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***Abstract*-The groundwater resource is crucial for water supply, irrigation and urbanization. Accurate assessment of recharge and prediction of future groundwater levels in groundwater system is vital for water management in a particular area. Recharge, as an input to groundwater model, is usually some fraction of rainfall. However, recharge is affected by spatial and time varying events on the surface. The present study demonstrates use of Arc SWAT model for water surface simulation and the estimation of recharge rates. The recharge values estimated using Arc-SWAT model are inputs to Visual MODFLOW groundwater system simulation model, parametric sensitivity analysis with hydraulic conductivity value performed. Calibrated and validated model further employee for future groundwater levels predictions in potential groundwater management scenarios. Methodology employed in Sai-Gomti interfluve region in India.**

Keywords- Groundwater Simulation; VISUAL MODFLOW; Sai-Gomti Interfluve; Uncertainty Analysis

I. INTRODUCTION

The high rate of increase in population and consequently overexploitation of groundwater resulted in a decrease in groundwater tables all over the world. Earlier, surface water and groundwater were managed separately [18]. Unsaturated zone of aquifer, which separates surface water and groundwater. A recent trend is to consider interaction surface of water components such as rivers or streams, lakes etc. with groundwater [7]. In this scenario of declining groundwater level, it is imperative to investigate the groundwater system on respect to recharge, withdrawal and storage capacity and groundwater system modelling for groundwater management. Understanding the interaction between surface water and groundwater is key to effective groundwater management strategy. Models predictive reliability is tested by proper assessment of recharge in space and time [16].

Simulation models simulate surface water and groundwater processes and their interactions. Chakravorty et al. (2014) used groundwater simulation model to investigate changes in waterlogged area by adopting conjunctives uses in lower Gandak basin of Bihar [6]. Alam and Umar (2013) applied MODFLOW simulation model to simulate groundwater in Hindon-Yamuna interfluve region, western Uttar Pradesh [3]. Gosh and Kashyap (2012) utilized optimization technique in pre-calibrated simulation model of groundwater flow [8]. Optimized sustainable groundwater extraction management of Lucknow city was carried out by Singh et al. (2013) [15].

Ahmed et al. (2008) investigated water balance in Krishni-Yamuna area in Uttar Pradesh, India [2]. Local scale groundwater flow model was developed by Palma and Bentley (2007) for groundwater resources management [11]. Groundwater system modelling of Azraq basin, Jordan was performed by Abdulla et al. (2000) [1]. Rodell et al. (2009) used GRACE Satellite data for assessment of groundwater depletion in India [13]. Groundwater conditions in North India were explored by Pradhan (2014) using GRACE data [12]. Tangdamrongsub et al. (2016) used GRACE satellite data to quantify total water storage and flood events over Tonlé Sap basin, Cambodia [17]. Guidelines are available for estimation of recharge in literature (Scanlon et al. 2002 [14]; Sophocleous, 2004 [16]). In present study, recharge from surface water to groundwater is quantified by semi-distributed Arc SWAT model. Subsequently, this recharge value is input to Visual MODFLOW groundwater simulation model. This methodology has been applied in Sai-Gomti interfluve region which is a part of Indo-Gangatic alluvial plain in Uttar Pradesh, India.

II. STUDY AREA

The study area is shown in Fig. 1. The study area is part of Uttar Pradesh in India comprising districts of Barabanki, Raebareli, Sultanpur, Pratapgarh and Jaunpur, India. The study area lies between latitude $25^0$41’60” N to $26^0$45’36” N, and longitude $81^0$6’36” E and $82^0$49’12” E and is estimated to be 8287.50 km^2. The area is representative of the whole of the Sarda Sahayak Canal command. It is expected that the methodology adopted and conclusions arrived, would be applicable elsewhere in the canal command area. The study area is interfluve bounded by Gomti and Sai rivers in north and south directions respectively. The confluence of Sai-Gomti River in Jaunpur district forms an eastern extremity of the area.

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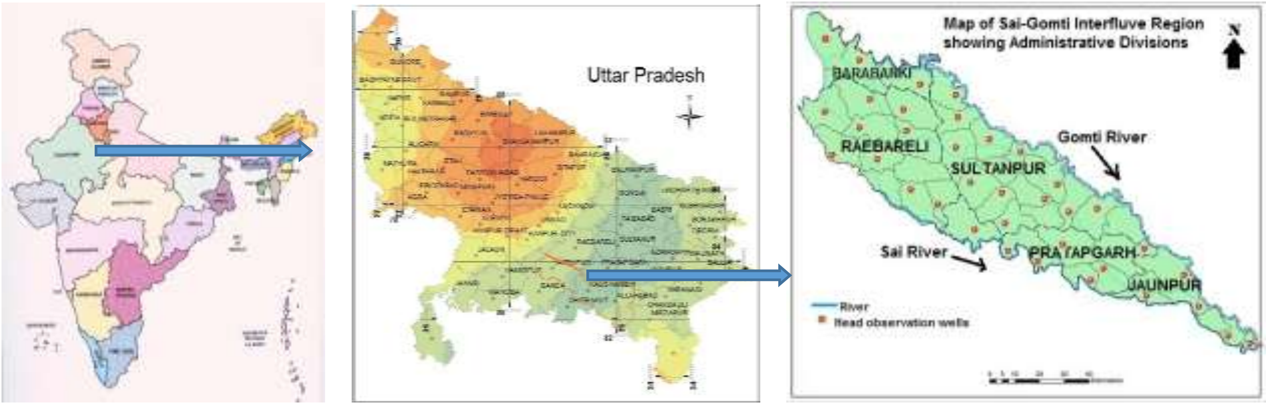

(a) (b) (c)

Fig. 1 Location map study are: (a) India (b) Uttar Pradesh (c) Study area

III. GEOLOGY OF STUDY AREA

The Sai-Gomti inter-fluvial plain is a part of central Ganga alluvial plain. It is laid by soft/ unconsolidated sediments. The soft sediments have assumed an enormous thickness which varies from place to place. The observations of deep drilling study conducted by CGWB [5] indicated that it is 487m thick at Janauli in Raebareli district where granite basement encountered; 399m at Kandhai in Pratapgarh district (Vindhayan sandstone as a basement) and 745m at Leduka in Jaunpur district. The alluvium an comprises alternation of sand-silt-clay sequence, sometimes the sequence gets admixed with concentrations of calcium carbonate or Kankar as called in a local language.

IV. GROUNDWATER SYSTEM SIMULATION

A. Groundwater Flow Model

Groundwater system is simulated using the following 3-D partial differential equation (1):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial x}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \quad (1)$$

Where, x, y, z are 3-D axes in Cartesian coordinate system, h = head [L], K_{xx}, K_{yy}, K_{zz} = hydraulic conductivities along x, y and z axes [LT^{-1}], W = volumetric flux/unit volume and represents sources and/or sinks of water [T^{-1}], S_S = specific storage of the porous material [L^{-1}], and t = time.

Visual MODFLOW three-dimensional finite-difference groundwater flow model is employed to simulate the groundwater flow system [10]. A single layer groundwater flow model has been developed based on the available information related to aquifer characteristics, rainfall, and other data sets of the study area. The total area of 8287.50 km^2 in Sai-Gomti interfluve region has divided into equal sizes grid network of 30 columns and 86 rows. Thus, the area has been divided into 2580 cells of equal dimensions. Each cell measures 2500 meters in length and with identical width. Hence, each cell represents 6.25 km^2. The input value of hydraulic conductivity (K) taken as 7.0 m/day and specific storage value of 0.001/m with a coefficient of storage (S) as 0.15. After the parameter estimation (PEST) run these values modified as hydraulic conductivity (K) = 6.005 m/day and specific storage value of 0.900/m with a coefficient of storage (S) as 0.16. The stress period of 8 years i.e. from the year 2005-2013 has considered.

River Sai and Gomti River have been assigned River Boundary Condition. A cluster of few grid cells in a western part of the area are simulated as General Head Boundaries, as either of the rivers does not bound these grid cells. The recharge calculated by calibrated Arc SWAT model i.e. 209 mm/yr was utilized for assigning the recharge value in Visual MODFLOW model. The groundwater levels in specified well locations for the period 2005-2013 was obtained from Central Ground Water Board (CGWB), Lucknow.

B. Subsurface Flow and Recharge Estimation Using Arc SWAT

Arc SWAT is a semi distributed physically based watershed simulation model. Basic components of SWAT are weather, hydrology, soil, and temperature and land use land cover (LULC) data sets. A watershed divided into sub watersheds, and sub watersheds are further subdivided into HRUs (Hydrologic Response Units). The HRU consist of similar soil and land use management characteristics. Critical hydrologic processes in SWAT model is represented by equation (2):

$$SW_t = SW_o + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right)0_i \quad (2)$$

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where t= time in days, SW_t and SW_o = the final and initial soil water content respectively (mm), R_{day} = amount of precipitation on day i (mm), Q_{surf} = the amount of surface runoff on day i (mm), E_a = the amount of evapotranspiration on day i (mm), w_{seep} = is the amount of water entering the vadose zone from the soil profile on day i (mm) and Q_{gw} = the amount of return flow on day i (mm).

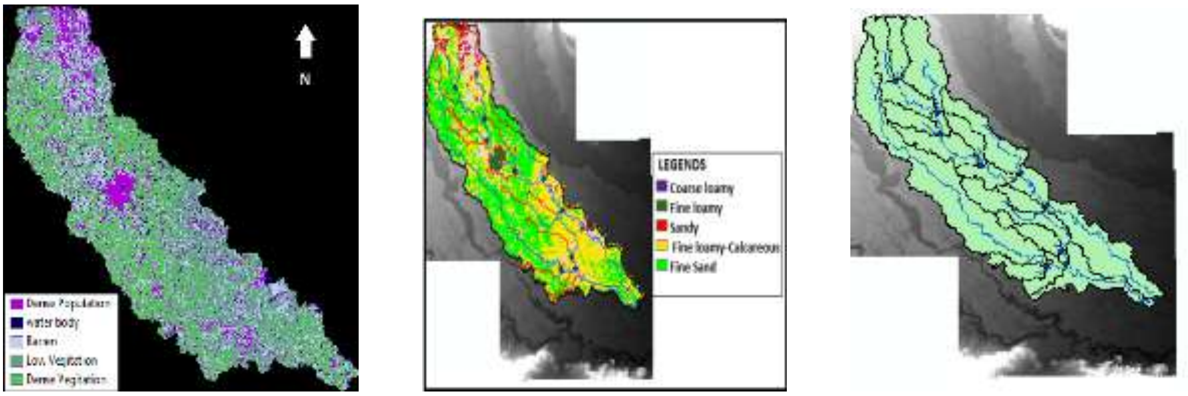
The estimation of surface runoff can be performed by the model using the SCS (Soil Conservation Service) curve number method. The SCS curve number is as given by equations (3) and (4):

$$Q_{surface} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \tag{3}$$

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{4}$$

where $Q_{surface}$ = the daily surface runoff (mm), R_{day} = the rainfall depth for the day (mm), and S= the retention parameter (mm), CN=curve number.

The SRTM DEM data of 90 m resolution processed. Also, the satellite imageries obtained from USGS Earth-explorer were processed for Land Use Land Cover (LULC) data using ERDAS Imagine software. Land use and soil classes were overlaid to define the HRUs for in sub-watersheds for the SWAT model as shown in Fig. 2.



(a) LULC Map (b) Soil Map (c) Delineated Watershed

Fig. 2 Watershed Delineation using arc SWAT

The weather data (Temperature and Rainfall) of the study area utilized for the period 1971- 2002. One year warm-up period is considered. The calibration of SWAT model was performed using SWAT-CUP tool. The SUFI-2 method utilized for calibration purpose. Based on the inputs provided, the Sai-Gomti basin was delineated and subdivided into 21 sub basins and 82 HRUs. The calibrated model validated with the available data sets of the year 2003-2005 and a good match observed as shown in Table 1.

TABLE 1 COMPARISON OF CALIBRATION AND VALIDATION PERFORMANCE STATISTICS DURING CALIBRATION (1971-2002) AND VALIDATION PERIOD (2003-2005)

Sr. No.	Parameter	Calibration	Validation
1	R^2	0.78	0.72
2	Nash-Sutcliff coefficient	0.75	0.71

This ArcSWAT model further utilized for prediction of recharge in Sai-Gomti basin over the period 2006-2012. The weather data for the period 2006-2012 obtained from India Meteorological Department (IMD), Pune. The results showed that the annual groundwater recharge rate varies between 15.96% (88.41 mm) to 23.25% (209.45 mm) of annual precipitation, which is close to Ground Water Estimation Committee (GEC)-1997 recommendations i.e. 20-25% of rainfall.

V. GROUNDWATER MODEL CALIBRATION AND VALIDATION

The groundwater system simulation model Visual MODFLOW has calibrated in both steady state and transient state for the period 2005-2012.

A. Steady State Calibration

November 2005 is considered to be in steady state. For this time, 36 observation wells in the study area are founded. The correlation coefficient and RMS values for observed and simulated are compared [4]. Mean error and correlation coefficient are 0.005 m and 0.94 respectively. The absolute residual mean is 0.056 m.

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B. Transient State Calibration

The model calibrated in transient state from 2005 to 2012 (7 years). The mean error is 0.442 m. The calibrated model provided hydraulic conductive (K) value as 6.005 m/d and coefficient of storage (S) as 0.23.

C. Model Validation

The calibrated model validated with the available data of the year 2013 and acceptable difference between observed and calculated values was observed. Fig. 3 shows a comparison between observed and calculated head values for the year 2013. The correlation coefficient value observed as 0.98.

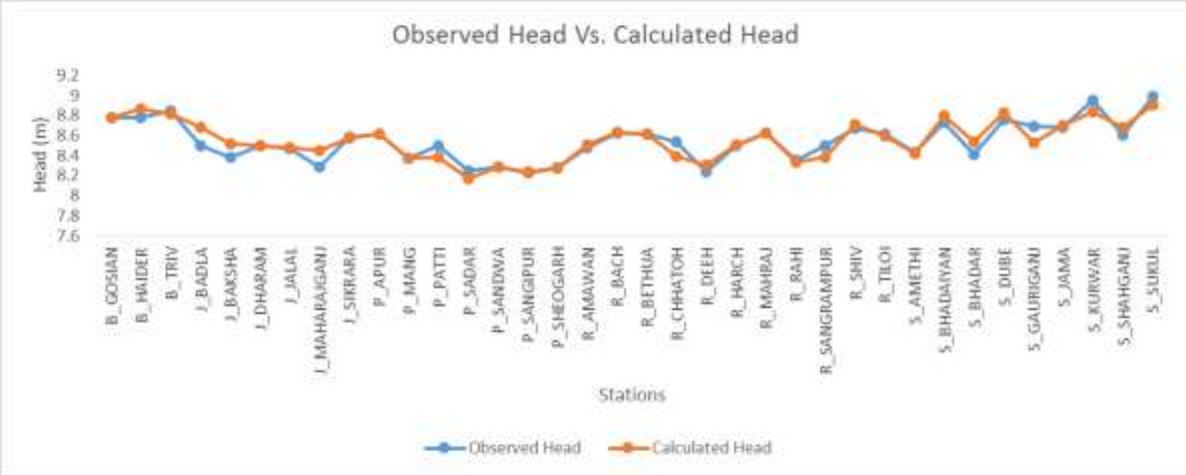

Fig. 3 Observed head vs. calculated head for the year 2013

VI. GROUNDWATER MODEL CALIBRATION AND VALIDATION

A. Sensitivity Analysis

The sensitivity analysis is performed to quantify the uncertainty in a calibrated model caused by an uncertainty in model and aquifer parameters [9, 4]. In the present study, the sensitivity of model on hydraulic conductivity was examined. The model runs with changes in hydraulic conductivity, and RMSE value was calculated comparing the observed head value and model simulated head values. The results obtained from sensitivity analysis (Table 2) with changes in hydraulic conductivity values up to ±15 percent revealed that the model is not much sensitive to hydraulic conductivity (K) values.

TABLE 2 SENSITIVITY ANALYSIS OF HYDRAULIC CONDUCTIVITY

Sr. No.	Variation in K	K (m/d)	RMSE (m)
0	No change	6.005	0.94
1	Increased by 5%	6.31	0.94
2	Increased by 10%	6.60	0.95
3	Increased by 15%	6.90	0.95
4	Decreased by 5%	5.71	0.92
5	Decreased by 10%	5.40	0.92
6	Decreased by 15%	5.11	0.91

B. Groundwater Management Scenarios

Calibrated and validated groundwater simulation model is further employed to predict groundwater management for potential scenarios. Three different scenarios considered for the Sai-Gomti interfluve region during 2014 to 2020.

1) Scenario 1: Constant Recharge and Increased Withdrawal Rate

In this scenario, the ongoing abstraction rate was increased by 20% during 2014 to 2020. The results showed that the areas nearby River Gomti are significantly affected. The blocks: Goasainganj, Trivediganj, Haidergarh, Jagdishpur, Sukul bazar have higher groundwater level ranging between 8.78 m to 8.82 m as shown in Fig. 4, against the groundwater level ranging from 7.43 m- 7.92m during the year 2013.

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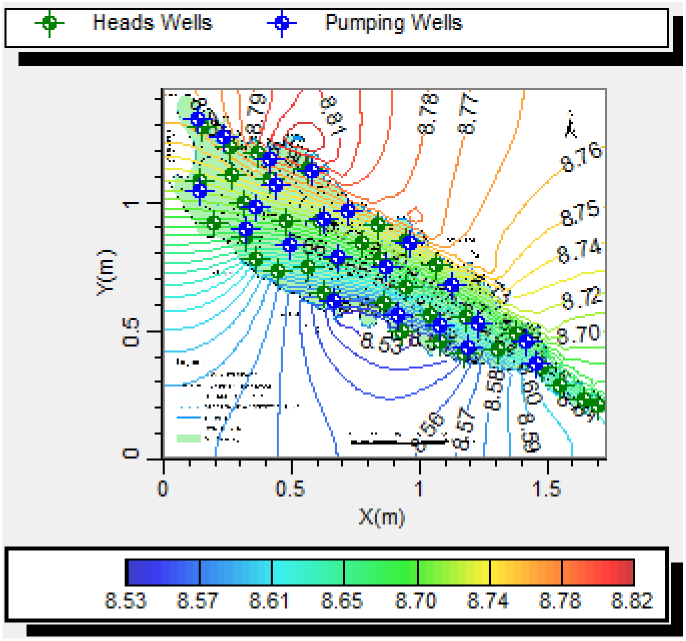

Fig. 4 Drawdown prediction in scenario 1

2) Scenario 2: Reduced Recharge and Increase Withdrawal Rate

In this scenario, combined effect of reduced recharge by 20 % and greater abstraction rate by 20%, was examined. It observed that the maximum groundwater level increased as compared to scenario 1. The maximum groundwater level of 8.81 m in Haidergarh block of Barabanki followed by Trivediganj Musafirkhana, Kurwar blocks of Sultanpur and Shivgarh, Singhpur blocks of Raebareli district (Fig. 5).

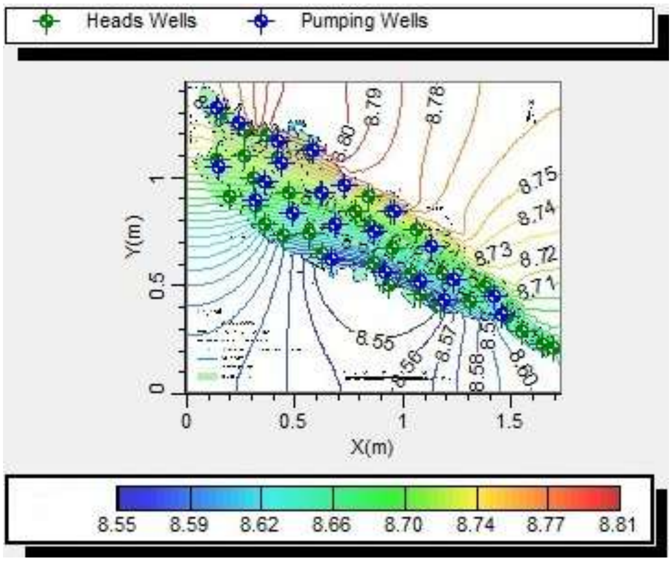

Fig. 5 Drawdown prediction in scenario 2

3) Scenario 3: Introducing Additional Recharge

To augment the depleting groundwater levels. The possible ways of augmentation may be construction of surface storage water structures and adopting water harvesting methods. An additional recharge of 100 mm/year is applied over the study area. The resulting simulation is sown in Fig. 6.

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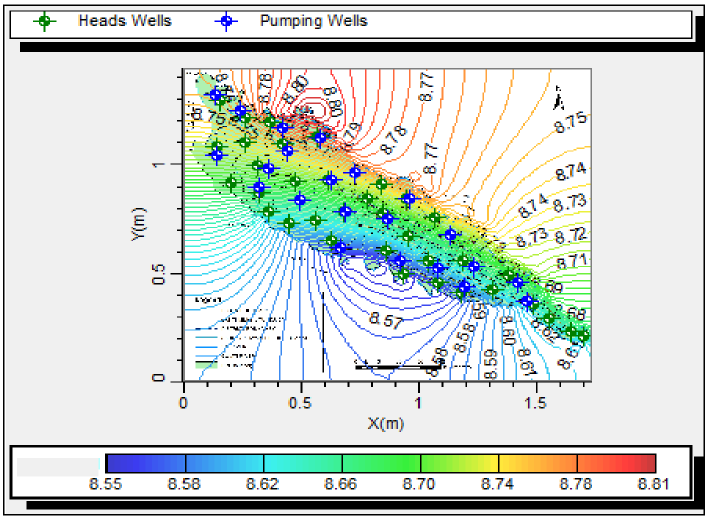

Fig. 6 Drawdown prediction in scenario 3

VII. CONCLUSION

Groundwater system for Sai-Gomti interfluve region is simulated using visual MODFLOW. Recharge input to the model is separately simulated using Arc SWAT. Sensitivity analysis results show that groundwater simulation model is tolerant up to 10% variation in hydraulic conductivity values after that simulation error increases. Three different scenarios of groundwater management are investigated based upon possible recharge and withdrawal patterns. The combined effect of reduced recharge by 20 % and increased abstraction rate by 20% were examined in scenario-2. The results suggest that the maximum groundwater level will reach 8.81 m in the year 2020. The areas close to Gomti River showed a high rate of decline in groundwater level i.e. Haidergarh block of Barabanki; Musafirkhana and Kurwar blocks of Sultanpur district, and Shivgarh block of Raebareli district. Therefore, artificial recharge and conjunctive use of water are suggested to mitigate the groundwater level decline. Also, enforcement some regulation on groundwater pumpage is highly needed for sustainability of groundwater resources.

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REFERENCES

[1] Abdulla F. A., Al-Khatib M. A., and Al-Ghazzawi Z. D., “Development of groundwater modeling for the Azraq basin, Jordan,” *Environmental Geology*, vol. 40, pp. 11-18, 2000.

[2] Ahmed I., and Umar R., “Hydrogeological Framework and Water Balance Studies in Parts of Yamuna- Krishni Interstream Area, Western Uttar Pradesh, India,” *Environ. Geol.*, vol. 53, pp. 1723-1730, 2008.

[3] Alam F., and Umar R., “Groundwater Flow Modelling Of Hindon-Yamuna Interfluve Region, Western Uttar Pradesh,” *Journal of the Geological Society of India*, vol. 82, pp. 80-90, 2013.

[4] Anderson M. P., and Woessner W. W., “*Simulation of flow and advective transport*,” Academic Press Inc., London, 1992.

[5] CGWB, “Annual report 2008-09,” *Central Groundwater Board India*, Ministry of Water Resources, Government of India, Tech. Rep., 2009.

[6] Chakravorty B., Pandey N. G., and Kumar S, “Effect of Conjunctive Use on Waterlogging in Lower Gandak Basin of Bihar,” *International journal of Scientific Engineering and Technology*, pp. 298-303, 2014.

[7] Dowlatabadi, S., and Zomorodian, S.M.A., “Conjunctive simulation of surface water and groundwater using SWAT and MODFLOW in Firoozabad watershed,” KSCE *Journal of Civil Engineering*, vol. 20(1), pp. 485-496, 2016.

[8] Ghosh S., and Kashayap D., “ANN-based model for planning of groundwater development for agricultural usage,” *Irrigation and drainage*, vol. 61, pp. 555-564, 2012.

[9] Kumar S. M., and Elango L., “Three dimensional mathematical model to simulate groundwater flow in the lower palar river basin, southern India,” *Jour. Hydrogeol.*, vol. 3, pp. 197-208, 2004.

[10] McDonald M. G., and Harbaugh A. W., “A modular three dimensional finite-difference groundwater flow model,” *USGS Open File Report*, pp. 83-875 USGS, Washington, D.C, 1988.

[11] Palma H. C., and Bentley L. R., “A regional scale groundwater flow model for the Leon Chinandega aquifer Nicaragua,” *Hydrogeology Journal*, vol. 15, pp. 1457-1472, 2007.

[12] Pradhan G. Understanding Interannual Groundwater Variability in North India using GRACE, MS Report, Univ. of Twente, Netherlands, 2014.

DOI: 10.5963/JWRHE0501003

[13] Rodell, M., Velicogna, I., and Famiglietti, J. S., "Satellite-based estimates of groundwater depletion in India," *Nature*, vol. 460, pp. 999-1002, 2009.

[14] Scanlon B. R., Healy R. W., and Cook P. G., "Choosing appropriate techniques for quantifying groundwater recharge," *Hydrogeology Journal*, vol. 10, pp. 18-39, 2002.

[15] Singh A., Burger M., and Cirpa A., "Optimized Sustainable Groundwater Extraction Management: General Approach and Application to the City of Lucknow, India," *Water Resources management*, vol. 27(12), pp. 349-368, 2013.

[16] Sophocleous M., "Groundwater recharge and sustainability in the high plains aquifer in Kansas, USA," *Hydrogeol Journal*, vol. 13(2), pp. 351-365, 2005.

[17] Tangdamrongsub N., Ditmar P. G., Dunne S. C., Gunter B. C., and Sutanudjaja, "Assessing total water storage and identifying flood events over Tonlé Sap basin in Cambodia using GRACE and MODIS satellite observations combined with hydrological models," *Remote Sensing of Environment*, vol. 181, pp. 162-173, 2016.

[18] Winter T. C., Harvey J. W., Franke O. L., and Alley W. M., "Ground water and surface water a single resource," U. S. Geological Survey Circular, 1139, Denver, Colorado, 79, 1998.

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