Modeling the potential for floodwater recharge to offset groundwater depletion: a case study from the Ramganga basin, India

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Abstract

The Ganges basin faces considerable spatial and temporal imbalance between water demand and availability. Lack of water storage infrastructure has led to this mismatch, wherein there are limited options to store flood water during the wet season and limited groundwater and surface water resources during the dry season. In this current study, a semi-coupled hydrological modeling framework is used to test scenarios that can help bridge this imbalance. A hydrological model (SWAT), groundwater model (MODFLOW) and flood inundation model (HEC-RAS) were applied to the Ramganga basin in India (~19,000 km^2) to understand the baseline hydrologic regime and to test scenarios with distributed managed aquifer recharge (MAR) interventions, which when applied to at the basin scale to co-address flooding and groundwater depletion has come to be known as Underground Taming of Floods for Irrigation. The scenarios with MAR, which used available basin runoff to recharge groundwater, yielded favorable results in flood reduction and groundwater level improvement throughout the sub-basin. Groundwater levels improved within 5 years of introducing MAR, resulting in a groundwater elevation increase of up to 7 m when compared to baseline conditions. The HEC-RAS model indicated that a 20% reduction in basin outflow converted a 15-year flood peak to an 8-year flood peak, a 5-year peak to 3 years and a 2-year peak to 1 year. In addition, this resulted in a 10% reduction in the inundated area in all return periods tested. Therefore, distributed MAR practices can be effective in reducing the negative impacts from larger return period floods and increasing the groundwater levels.

Key Words: Ganges basin; Groundwater depletion; Floods; Recharge; Managed aquifer recharge (MAR); Underground Taming of Floods for Irrigation (UTFI); India

Introduction

India is an agrarian nation which ranks second globally in terms of agricultural production (Shah 2010). Access to groundwater resources for irrigation is a key component and vitally important for food security and economic growth in the country. In recent years, due to increase in agricultural area, increase in climate variability and agricultural intensification activities, there has been tremendous stress in accessing groundwater for irrigation (Briscoe and Malik 2005). The Indian agriculture sector accounts for 60% of the total groundwater extraction, which is the highest globally (Shah 2010).Therefore, proper agricultural water management strategies are important to sustain the Indian agrarian community and in avoiding socioeconomic stress related to farming, especially in critical zones that are impacted by water stress. The Ganges river basin (GRB) is one such important region that supports a large number of farmers, but also faces water shortage issues during the dry season and flood issues during the wet season (Chinnasamy 2016a).

The GRB basin, with a total area more than 1,086,000 km^2, is transboundary in nature and runs across four South Asian countries: India, Nepal, Bangladesh and China. The Ganges River's origin is at the Gangothri Glacier, with an altitude of over 7000 m. The river traverses approximately 2000 km, enters the plains in Haridwar at an altitude of 100 m and then joins the Brahmaputra and Meghna rivers at a confluence point in Bangladesh. The monsoon rainfall provides most of the irrigation water for the monsoon season (June–October) crops. During the dry and hot season (November–March), due to limited rainfall, irrigation is needed to sustain perennial and non-perennial crop production. The total renewable water resources in the GRB amounts to about 552 km^3, of which about one-third is from groundwater resources. Amarasinghe et al. (2016) estimated that 20–40% of the renewable water resources in the basin are consumed annually.

In recent decades, groundwater irrigation has increased significantly in the GRB. The best yielding aquifers are located in the alluvial deposits of the Gangetic Plain in India (Saha et al. 2016). It is estimated that more than 60% of the irrigated agricultural production is supplied from groundwater resources (GoI 2009; World Bank 2010; Saha et al. 2016).Since the extraction rates are high, serious groundwater depletion has been observed in many regions of the GRB (ADB 2007; ADBI 2012). Many case studies have been conducted in India to study the groundwater depletion trends. Chinnasamy (2016b) used groundwater data from 152 monitoring wells, monitored by the Central Ground Water Board (CGWB) and remote sensing data from the Gravity Recovery and Climate Experiment (GRACE) satellite mission to understand the groundwater depletion trends in the Ramganga basin. He reported that, on average across the Ramganga basin, the GRACE analysis indicated that the groundwater was being depleted at 27 cm/year (equivalent to 1.6 billion m^3/year volume of water). Therefore, there is an ever increasing need to formulate groundwater management plans that can lead to a sustainable use and replenishment of the groundwater resources in the GRB.

Floods, one of the most common natural disasters in the GRB, are caused by intense seasonal monsoon precipitation and have been a recurrent phenomenon. Many studies indicated that the flood frequency and intensity in the Ganges have increased considerably over the past decade (Fushimi et al. 1985; Dhar and Nandargi 2002; Mool et al. 2001; Shrestha and Bajracharya 2013).

According to the Government of India (GoI), floods and droughts affect thousands of people and livestock and damage crops and properties worth millions of dollars (GoI 2015). In particular, floods mostly affect the eastern Ganges region, including the states of eastern Uttar Pradesh, Bihar, West Bengal and the Bangladesh riparian region (Chinnasamy 2016b; Muthuwatta et al. 2015; Amarasinghe et al. 2016). For example, the 2013 floods affected over 13.7 million people in the states of Bihar, Uttar Pradesh, Uttaranchal and West Bengal. This was almost two thirds of the total flood-affected population in India for the same year (GoI 2015). Moreover, the 2013 floods damaged crops and public and private utilities worth over USD 700 million in the four states. The 1970–1971 floods caused damages amounting to USD 479 million (at current prices) for entire India 1970–1971, which indicates the severity of recent floods (GoI 2015). As a result, there is a need to reduce flood damage, by investing in alternate water storage methods in the GRB region.

A new application of managed aquifer recharge (MAR) recently developed involves strategically recharging depleted aquifers in upstream regions of catchments with wet season high flows, thus preventing downstream flooding and simultaneously providing additional groundwater for irrigation during the dry season and drought-proofing communities. This MAR modality has been named “Underground Taming of Floods for Irrigation” or UTFI (Pavelic et al. 2015; Brindha and Pavelic 2015). Careful planning of UTFI is needed to ensure that upstream– downstream surface and subsurface flows and interlinkages are fully understood in advance to implementation. Water quality is an important consideration in the assessment of the viability of UTFI. This aspect is being addressed through ongoing parallel research at the pilot trial scale (Pavelic et al. 2015).

The primary objective of this study is therefore to investigate the potential for UTFI to offset groundwater depletion in the GRB. This analysis has been performed across one of its sub-basins: the Ramganga. To achieve this objective, a semi-coupled modeling framework was used, wherein a surface water model (SWAT) was used to assess the current and future hydrological regime of the Ramganga basin. A groundwater model (MODFLOW) was then used to test management scenarios based on UTFI that can result in reducing basin outflow and in improving groundwater storage. Finally, HECRAS (a flood inundation model) was used to understand potential changes in flooding extent, if any, under several futuristic scenarios.

Methods

Study site

The Ramganga River in India, with a total length of 595 km, is the first major tributary of the Ganges with a basin area of 18,668 km^2 (Fig. 1). The river flows across the states of Uttarakhand and Uttar Pradesh, along a topographic elevation ranging from 1000 to 2688 m above mean sea level (amsl) in the north to 124 m amsl in the south. The southwest monsoon delivers most of Ramganga’s rainfall over a period of 5 months (June–October).

The Ramganga basin is filled with extensive alluvial sediments. These sedimentary deposits form a thick set of unconfined and leaky aquifers with a thickness of 1,500 – 2,000 m and varying proportions of sand, gravel and pebbles. Such stratification has led to the formation of many layers of high-yielding aquifers (Prasad, 1990; Rao and Prasad, 1994; Surinadu et al. 2016; CGWB 2011).

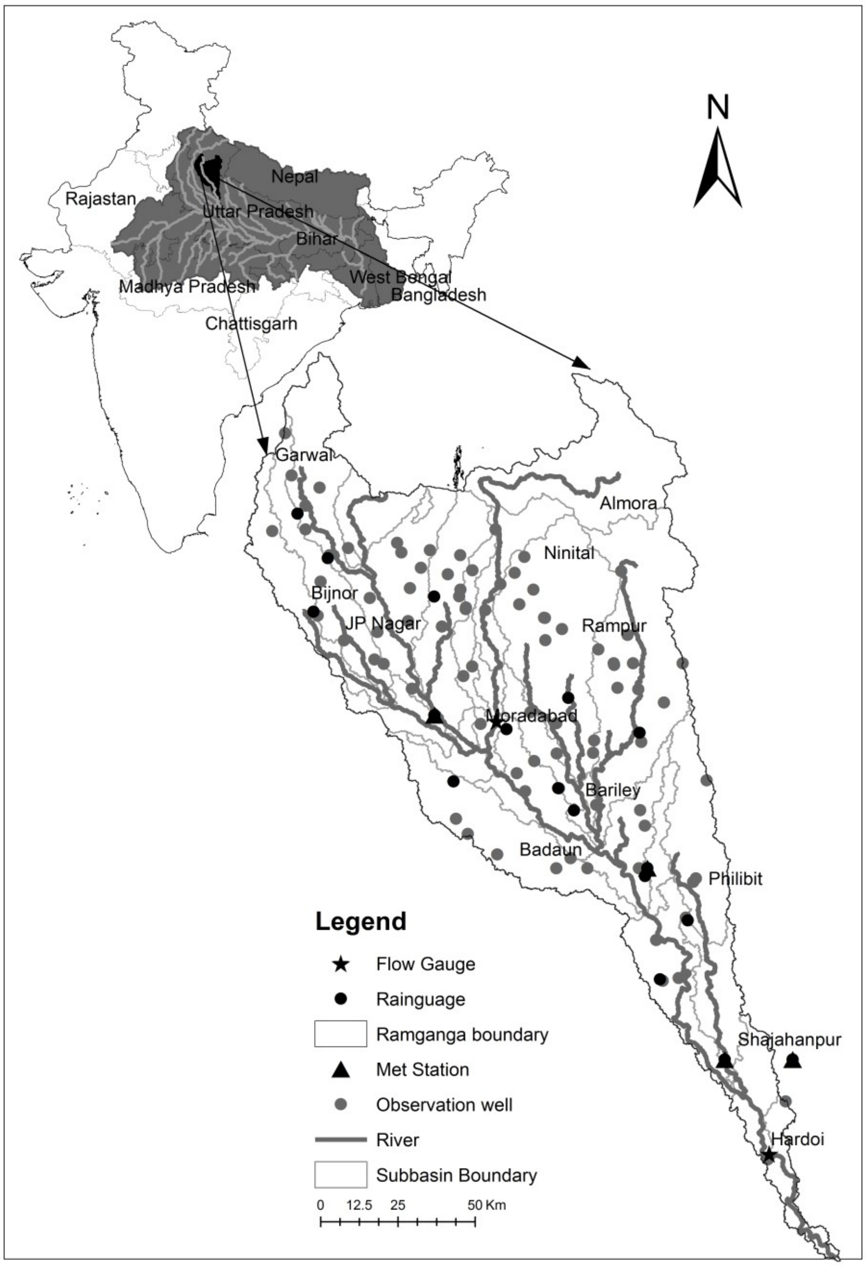


Figure 1. Location of the Ramganga basin indicating the location of observation wells, flow gauges, rain gauges and meteorological stations

Semi-coupled modeling framework

A semi-coupled method was used in this study as it built upon an already calibrated and validated groundwater model (Surinaidu et al 2016), along with a new surface water model, which was calibrated and validated independently. The semi-coupled modeling framework (Fig. 2) was adopted and improved from Surinaidu et al. (2016). As seen from the framework, individually calibrated surface hydrology model [Soil and Water Assessment Tool (SWAT)], groundwater model (MODFLOW) and flood inundation mapping model (HEC-RAS) were used to understand the current and future hydrologic regime in the Ramganga basin with an aim to identify scenarios that can improve groundwater storage and lessen flood damage in the basin. The inclusion of HEC-RAS modeling is a new aspect, when compared with the framework of Surinaidu et al. (2016), in assessing inundation area. Surinaidu et al. (2016) developed the Ramganga MODFLOW model and used futuristic scenarios from a SWAT model, without testing the flood inundation effect on upstream locations.

Initially, the SWAT model is used to quantify the surface hydrology components of the water balance including discharge, inflow, outflow, water yield, evapotranspiration and groundwater recharge. The calibrated and validated SWAT model's estimates of groundwater recharge and irrigation return flow are then used in the MODFLOW model to simulate groundwater flow. SWAT estimates recharge at the hydrologic response unit (HRU) level, while MODFLOW is a grid based model. Therefore, in the semi-coupled framework, the HRU estimates of recharge are disaggregated to the grid boundaries in the MODFLOW domain. Then, the averaged recharge estimates are imported into the MODFLOW grid base using the VISUAL MODFLOW model setup interface. This coupling is run several times by inputting the outputs from MODFLOW (e.g., groundwater pumping) into SWAT until the calibrated and validated results in MODFLOW are agreeable.

It is noted that the SWAT was calibrated using the observed streamflow and pertinent hydro-climatic data. On the other hand, the MODFLOW model was calibrated using the observed groundwater levels. This completes the framework for the hydrological assessment in the baseline scenario.

Once the SWAT and MODFLOW models were calibrated and validated separately, MODFLOW was used to analyze several pumping and MAR scenarios to assess their impact on groundwater levels and river flows at the basin level. The scenarios that are capable of improving the groundwater level status in the basin were then identified. Such identified scenarios were then tested in the HEC-RAS model to estimate the inundation extent under each scenario across the basin. Even though many scenarios were tested, in the interests of being concise only the successful scenarios will be discussed in detail herein.

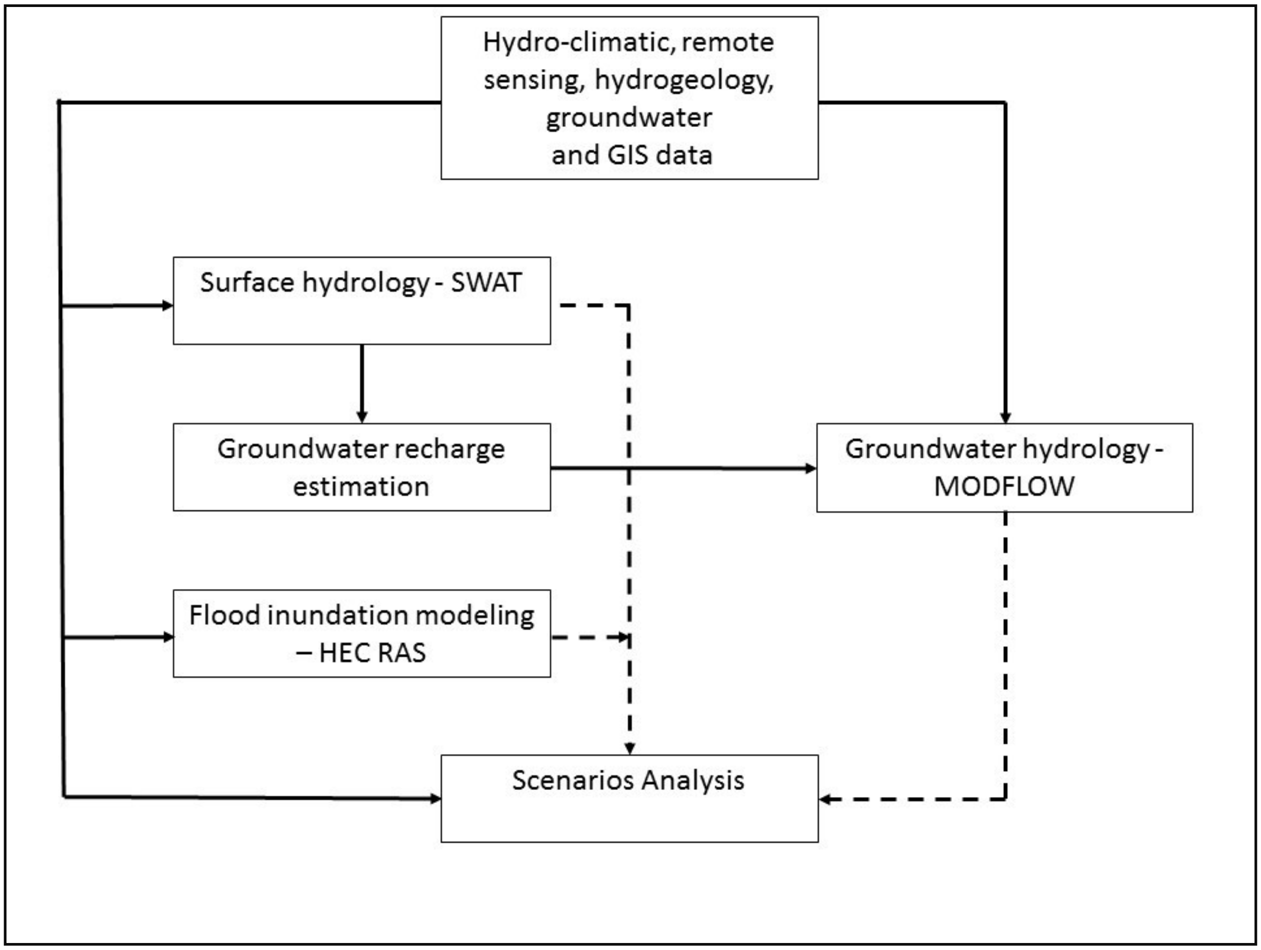


Figure 2. Semi-coupled framework for assessing surface water and groundwater interactions used to implement the scenarios

Scenario development

To satisfy the major objective of this study, i.e., to test scenarios that reduce flood discharge and improve groundwater levels via UTFI interventions, a number of scenarios were formulated and tested. The following scenarios were assessed in the current study:

Baseline scenario

This scenario is to understand the current hydrological regime, groundwater movement and flooded extent in the basin from 1999 to 2010. It establishes the baseline conditions against which the alternative management scenarios will be tested.

Distributed MAR scenario

As discussed earlier, MAR activities have been successful in increasing groundwater storage. However, the impact of these interventions on reducing floods is still not investigated. In this scenario, MAR interventions are introduced in the basin, using the groundwater model (MODFLOW) in an aim to reduce the overall surface runoff leaving the basin. The cumulative outflow leaving the basin, from sub-catchment 27 (Fig. 3), was estimated from the SWAT baseline model outputs. Then, a total of five scenarios with different levels of MAR were introduced in the model so that the annual average outflow discharge is reduced by up to 50%.

Model Setup and Testing

SWAT Model

SWAT Model setup

SWAT was used to simulate the hydrological variables in Ramganga basin (Arnold et al. 1998). Using the topographic data obtained from the Shuttle Radar Topographic Mission (http://srtm.csi.cgiar.org/), 27 sub-catchments were identified (Fig. 3). These sub-catchments were delineated automatically in SWAT using ArcGIS Spatial Analyst extension. Stream network was defined for Ramganga using the concepts of flow direction and flow accumulation. The size of these sub-catchments ranged from 30.5 to 2271 km^2. The input precipitation data were derived from 18 meteorological stations located within the basin and the other meteorological data were available only at four stations. By using the Thiessen polygon technique, the average daily precipitation for each sub-catchment was estimated. The soil and land use maps were obtained from the National Institute of Hydrology and the Indian Institute of Technology (Delhi), respectively. The major data sets used in this study are listed in Table 1.

Table 1. An overview of the main data sets used in the SWAT model

Category	Data (resolution)	Data source
Topography	Digital elevation model (DEM) (90 m × 90 m)	Shuttle Radar Topography Mission (SRTM)
Land use	Land use map (30 m × 30 m)	Satellite-based land use map developed by National Institute of Hydrology, India
Soils	Digital map of the soils and soil properties (90 m × 90 m)	Indian Institute of Technology, Delhi, India
Climate	Rainfall, temperature, relative humidity, sunshine hours, wind speed (daily)	National Institute of Hydrology, India
River flow	Monthly river flow	National Institute of Hydrology, India

Calibration and validation of SWAT

The SWAT Calibration and Uncertainty Program (SWATCUP) (Abbaspour 2009) was used to calibrate the model. Data from a flow gauging station, Dabri, located near the outlet of the Ramganga basin, were used for the calibration. Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970) and the coefficient of determination (R^2) were used to evaluate model performance. During the calibration process, model parameters were systematically adjusted to obtain results to match the observed values reasonably. In the validation process, the catchment responses were simulated with the final parameter set obtained during the calibration process without any change and the computed hydrographs were compared with the observed hydrographs to evaluate of the performance of the model. The calibration period was selected as 1994– 2002 with the first 2 years set as a warming up period. The calibrated model was validated for the period 2003–2010. Flow data required to calibrate and validate the model were available at the National Institute of Hydrology (NIH)-Roorkee, India. Therefore, the NIH conducted the calibration and validation.

The SWAT calibration and validation exercises yielded satisfactory (in modeling terms) results. The performance indicators, NS and R^2 were 0.57 and 0.69, respectively, for the calibration period and indicate reasonable agreement between the observed and simulated streamflow time series. For the validation period, NS and R^2 were 0.80 and 0.85, respectively. Of the key parameters, the calibrated and validated model used 73 for curve number (calibration range 35–98), 0.97 for soil evaporation compensation factor (calibration range 0–1), 0.039 for groundwater "revap" coefficient (calibration range 0.02–0.2) and 0.9 for plant uptake compensation factor (calibration range 0–1).

MODFLOW groundwater model

MODFLOW model setup

The MODFLOW simulation model has been successful in modeling the groundwater regime in complex groundwater systems in the Indian subcontinent (Tamma Rao et al. 2012; Surinaidu et al. 2014). The Ramganga groundwater flow model for the current study was developed with MODFLOW 2005, using Visual MODFLOW 2011 as a graphical interface (Waterloo Hydrogeologic 2011).

Information from geological, hydrogeological and climatic parameters was used to set up the conceptual MODFLOW model for Ramganga. Due to the limitations in groundwater level observation data and geological investigation records, the Ramganga MODFLOW model for, baseline scenario, excluded higher elevated portions (mostly with elevation greater than 500 m), as these regions were characterized by consolidated and hilly geological settings where observation data were limited (Fig. 1). The MODFLOW modeling was done only for the unconsolidated portions of the sub-basin, which had better data for the model setup and calibration (Surinaidu et al. 2016).

Lithological data from 140 bore well records in the study area were used to conceptualize the alluvial aquifers of the Ramganga basin as a two-layer aquifer model with 500 m^2 resolution. The first layer consisted of clay with silt and sand, while the second layer consisted of sand with gravel and boulders with occasional clay. The first layer was delineated as the unconfined aquifer (with thickness ranging between 16 and 124 m), while the second layer was delineated as a semiconfined/unconfined (with thickness ranging from 192 to 86 m) aquifer. In the absence of further information, the total thickness of the two aquifers was kept at 210 m. Digital elevation models (DEM) were used to model the surface of the unconfined aquifer, in an assumption that the aquifer followed the normal topography. The DEM was derived from the Shuttle Radar Topography Mission (SRTM) 90-m resolution data (http://srtm.usgs.gov/), which was smoothened to 500 m^2 in the MODFLOW model.

Once the model structure was developed, the aquifer properties were assigned. Aquifer parameters were derived from literature published for the Ramganga area (Revelle and Lakshminarayana 1975; Umar 2014; Ahmed and Umar 2009; Khan et al. 2014). Since there was variation in the aquifer properties between studies, the values were used to assign a range, which was later adjusted during model calibration. The river boundary condition from the river package of MODFLOW was used to capture the hydrological interactions between the river and the aquifer. Groundwater head data were used to set up constant head boundary conditions, which were used to simulate lateral groundwater inflow from the northern part of the basin and resulting outflow from the basin. Since the SWAT model results were to be coupled with the MODFLOW grids, the groundwater recharge estimated from the SWAT simulation was used as input in the recharge package for the MODFLOW model. The Visual MODFLOW interface was used to simulate the groundwater balance using the zone budget module. It is to be noted that the zone budget module estimates water fluxes from different hydraulic components, such as recharge, inflow, outflow, river discharge, groundwater head and river and aquifer interactions (Waterloo Hydrologic 2011).

Calibration and validation of MODFLOW

The groundwater flow model has been calibrated simultaneously under transient conditions from 1999 to 2005 by considering the steady-state model parameters as initial conditions. The time was divided into 14 time steps with two stress periods per year. The model was calibrated by adjusting only two parameters: the hydraulic conductivity and specific yield. Groundwater levels measured from 150 observation wells were used for calibration. As indicated in the previous section, the ranges for hydraulic conductivity and specific yield were assigned from secondary sources and literature. It was noted that the conductivity in the river was assigned higher than other values. Then through rigorous trial and error calibration method, the hydraulic conductivity and specific yield values were adjusted [e.g., by decreasing by 25% (16– 12 m/day) along the river, increasing aquifer conductivity by three times in the second layer (from 16 to 36 m/day), etc.]. On the other hand, the specific yield of the aquifer was increased up to 16% and 25% for first and second layers, respectively. The performance of calibration was assessed using the root-mean-square (RMS) method and normalized root-mean-square (NRMS) errors method (Anderson and Woessner 1992). More information on the sensitivity analysis performed on the baseline model can be obtained from Surinaidu et al. (2016).

The calibration model runs yielded RMS of 4.6 m, NRMS of 2.7% and standard error of the estimate (SEE) was 0.028 m. Once the model was simulated and values were adjusted for the calibrated period, Surinaidu et al. (2016) validated the model for the period from 2006 to 2010. Their validation results indicated that the analysis between observed and modeled results were a ‘good match’, with simulated results indicating RMS and NRMS of <5 m and <3%, respectively. During the validation period, the average values for RMS, NRMS and SEE were 4.1 m, 2.3% and 0.042 m, respectively.

More information on the calibration and validation process and results can be obtained from Surinaidu et al. 2016. Of the key parameters, the calibrated and validated model used 12 m/day for the hydraulic conductivity in the x and y axis (range tested from 1 to 100 m/day), 1.2 m/day for the hydraulic conductivity in the z axis (0–50 m/day tested), 0.16 for specific yield (0–0.5 tested) and 0.00045 m^{-1} for specific storage (0.0002–0.002 m^{-1} tested). The MODFLOW model was then used to assess the baseline conditions of the model domain.

Under the scenario in which outflow is reduced by storing the water through MAR, the MODFLOW model was run for each sub-scenario to understand which had the best influence on the groundwater levels across the basin. Three well locations were chosen that represented upstream (well 1), middle (well 2) and downstream (well 3) sections of the basin (Fig. 3). MODFLOW was run for each sub-scenario and outputs were extracted at each representative well location to understand the impact on groundwater resources.

HEC-RAS model

The HEC-RAS model, developed by the Hydrologic Engineering Centre of the US Army Corps of Engineers (USACE 2016) was used to model the hydrodynamics of the major tributaries of the Ramganga basin. The model was used to simulate the river water level profiles along the river network and map the inundated area under different return period floods considering baseline conditions and future groundwater recharge scenarios (explained in Sect. "Scenario development"). Annual peak flows generated by the SWAT model (Sect. "SWAT model") were used as flow input to the HEC-RAS model. The major stream geometry and the cross section geometry (at 7 km intervals) along the streams were generated using a digital elevation model (SRTM 90 m resolution) and the HEC-GEORAS software (USACE 2016).The river network coincides with the river network and sub-basin divisions of the SWAT hydrological model (Fig. 3).

The annual peak flows (from 1994 to 2010) generated by the SWAT model at key locations on major streams of the Ramganga basin were fed into the HEC-RAS model considering the water level at the outlet of the Ramganga basin (simulated by a previous HEC-RAS model for the entire Ganges basin) as the downstream boundary condition. The model for the entire Ganges basin has been previously set up and calibrated and validated for the period 1987–1999 using satellite altimetry derived river water levels at three locations of the basin. The main input parameters governing the water level at each cross section of the river network of the Ramganga model are Manning's n and contraction expansion coefficients. Typical Manning's n values for natural channels were obtained from Chow (1959) and the values used ranged from 0.01 to 0.36. A contraction coefficient of 0.1 and an expansion coefficient of 0.3 were also used. They are the same parameter values that had been used in the calibrated model for the larger Ganges basin.

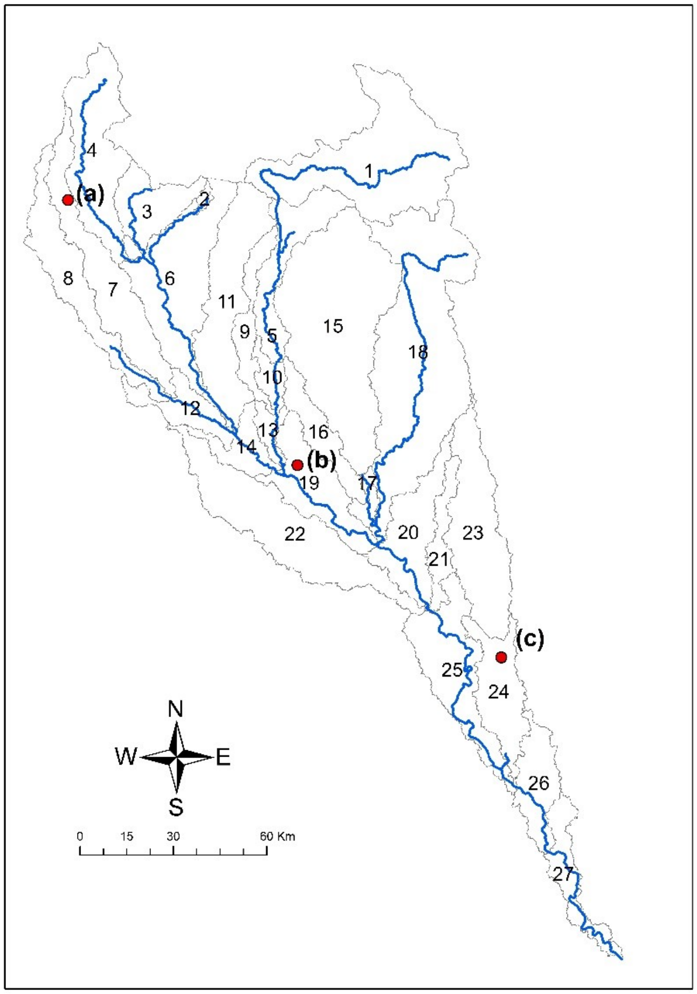


Figure 3. River network geometry of the HEC-RAS model for Ramganga basin. The *red dots* indicate the location of the three reference wells (*a* upstream well, *b* middle well and *c* downstream well)

Results and Discussion

Surface water yield results

Figure 4 shows the monthly flow at the outlet of the Ramganga basin from 1999 to 2010. The average monthly flow is about 559 million cubic meters (MCM) and the maximum flow occurs during the July to September period. In September 2010, the maximum flow went up to 5305 MCM. As shown in the figure, in most years the maximum flow fluctuates around 2000 MCM. The lowest maximum flow which is about 1272 MCM occurred in July 2006.

The average outflow volumes from the Ramganga during July to September was about 5782 million cubic meter (MCM/season) and ranges from 2703 to 12,283 MCM/season. More than 80%

of annual outflow occurs during July to September. Therefore, reducing outflow in these 3 months, for instance, by 20% generates about 542 MCM in dry years, while this volume goes up to 2457 MCM in a wet year. The average would be about 1156 MCM. This volume is spatially distributed among all of the sub-catchments. To model the reduced outflow scenarios, the ratios of total water yield to the individual sub-catchment water yields were used. It is assumed that the reduction of the flow at sub-catchments is directly proportional to the water yield in the respective sub-catchment. Table 2 presents the estimated water volume reductions during the peak flow months from the different sub-catchments. In other words, by recharging these volumes, the overall basin outflow can be reduced by 20%.

Spatial distribution of the outflow reduction provides important information in terms of water availability for MAR in the different sub-catchments. This can be used to formulate MAR strategies for the sub-basin. For instance, depending on the water available in certain sub-catchment, it is possible to decide what kind of physical structures are required to implement MAR in different sub-catchments. However, the siting and design of MAR depends on the number of other local factors such as land availability, community interest, aquifer capacity, the nature of any hydraulic connection between the aquifer and river when groundwater levels rise by the degree predicted and more. Therefore, it needs additional investigations as have been conducted in sub-catchment 14 (Pavelic et al. 2015).

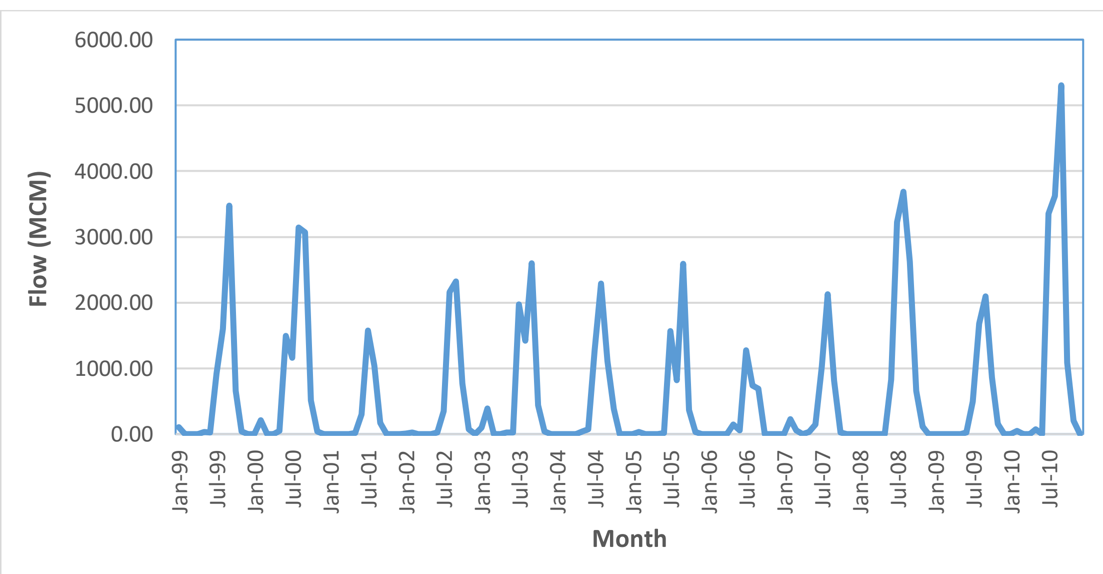


Figure 4. SWAT model simulated streamflow at the most downstream outlet of the Ramganga basin

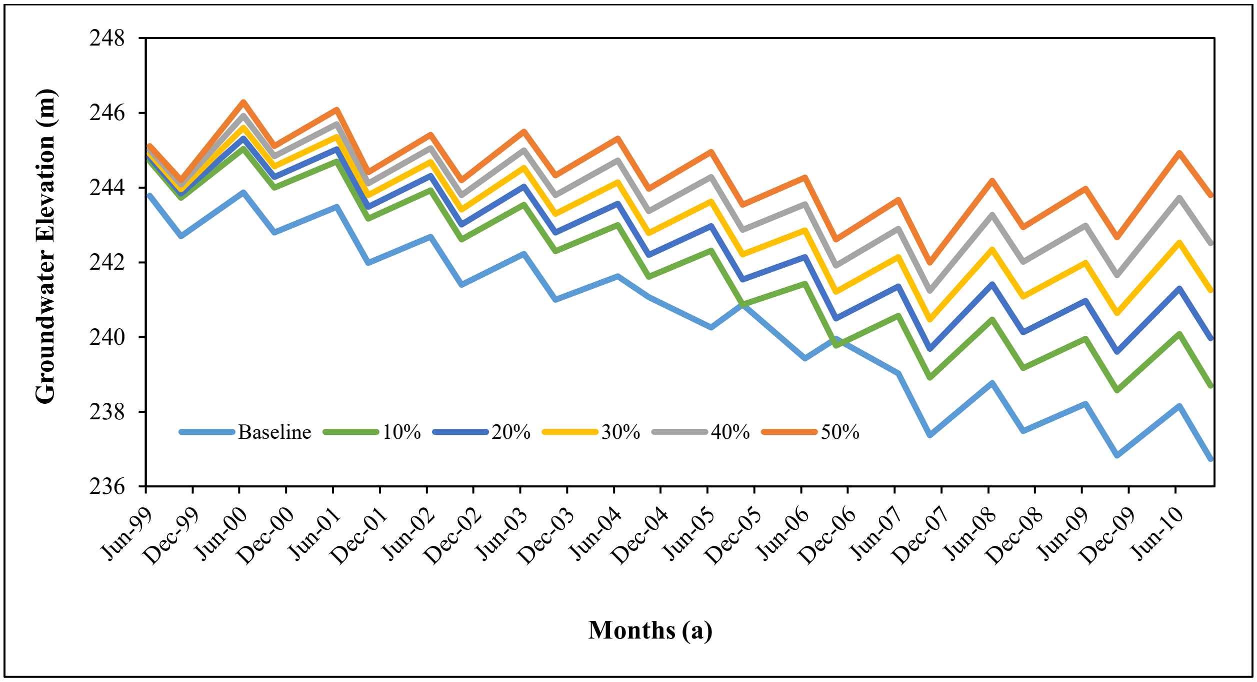
Table 2. Distribution of sub-catchment outflow reduction (in MCM) at Ramganga basin when 20% of the basin outflow is reduced from July to September

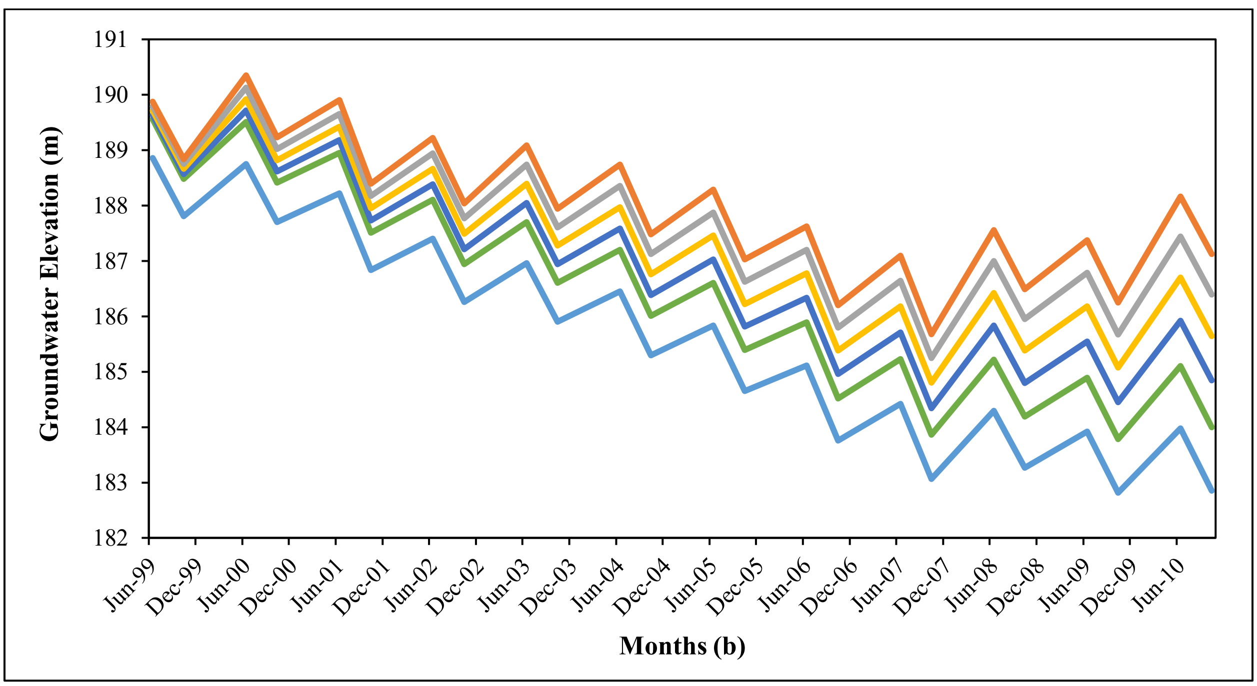
Sub-catchment	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Average	SD
1	59	31	8	19	20	27	23	4	17	59	14	101	32	27
2	61	14	3	2	4	10	17	0	2	24	5	103	20	30
3	86	106	43	44	66	58	83	43	46	80	54	106	68	23
4	91	113	39	72	109	79	108	65	73	70	35	152	84	32
5	68	23	10	5	5	11	20	2	6	38	12	113	26	32
6	59	40	15	12	19	24	29	4	16	45	22	107	33	27
7	63	91	34	47	79	53	62	39	46	67	45	106	61	21
8	62	87	35	48	80	54	64	39	48	68	43	107	61	21
9	19	7	0	7	12	5	12	1	18	63	20	74	20	23
10	19	6	0	7	11	5	11	1	15	60	19	72	19	22
11	60	40	15	12	20	25	30	4	17	47	22	110	34	28
12	66	68	32	41	81	78	69	38	54	44	47	141	63	28
13	18	5	0	9	14	5	11	1	17	64	20	70	19	22
14	55	68	35	48	84	67	63	8	22	36	30	119	53	29
15	71	66	22	65	47	56	33	14	49	111	40	93	56	27
16	17	33	3	29	13	23	24	2	18	78	25	68	28	22
17	25	67	26	80	25	53	43	19	29	112	27	94	50	30
18	71	93	26	67	78	64	52	26	71	160	71	143	77	38
19	22	58	13	53	20	44	37	4	19	88	28	75	38	25
20	25	67	28	81	25	53	43	19	28	112	27	94	50	30
21	52	95	36	45	73	32	49	40	45	86	44	75	56	20
22	44	69	37	54	73	57	51	7	19	62	26	93	49	23
23	52	95	36	38	73	32	39	40	45	86	41	74	54	21
24	7	32	14	16	39	4	5	27	10	45	21	25	21	13
25	6	32	13	15	37	4	5	27	10	44	21	24	20	13
26	9	31	16	24	45	6	4	27	25	78	47	58	31	21
27	12	34	18	24	45	6	8	36	27	80	48	60	33	21
Total	1199	1474	556	966	1199	937	996	540	793	1907	854	2457	-	-

SD – Standard deviation

Groundwater model results

The groundwater level trends for each scenario, at each of the three reference well locations (shown as *red dots* in Fig. 3), are shown in Fig. 5a–c.





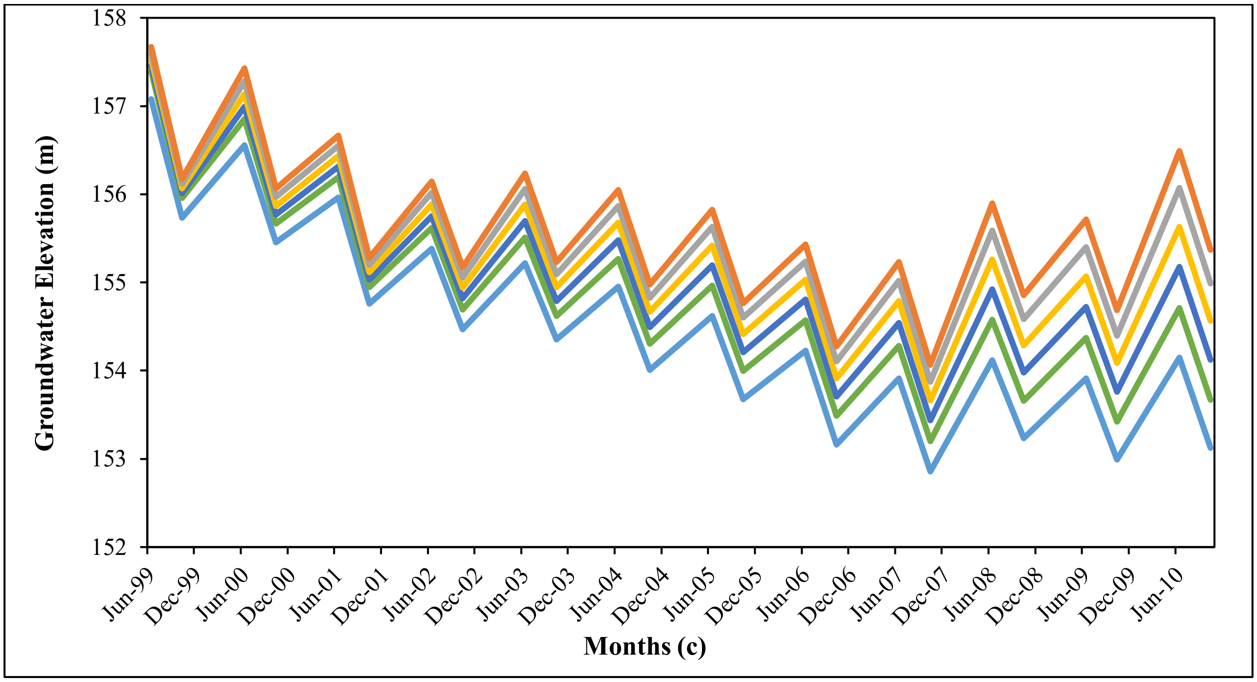


Figure 5. Groundwater level elevation graphs under the reduced basin outflow scenario for each well location (*a* upstream well, *b* middle well and *c* downstream well). Each sub-scenario represents the percentage by which the basin outflow was reduced. A maximum of 50% was reduced (*orange line*) and each sub-scenario was compared against the baseline condition (*blue line*)

The results indicate that, with the reduction of basin outflow and use of the reduced volume in upstream groundwater recharge activities, there is a considerable change in the groundwater depletion trend. If these scenarios had been introduced in 1999, within 10 years, all would indicate a trend in which the groundwater levels stabilize and find new equilibrium levels. In some cases (e.g., 50% flow reduction), the groundwater trends stabilize and increase. This indicates that the current water demands are satisfied and excess water is available to recharge the groundwater and keep the groundwater storage at above average conditions.

After 10 years, the maximum difference in groundwater level of 7 m is evident in the upstream locations for the 50% reduced runoff scenario when compared against the baseline conditions. Even the lesser reduction scenarios reported higher groundwater levels when compared against baseline conditions. In the upstream locations, the 40, 30, 20 and 10% scenarios indicated 6, 5, 3 and 2 m higher groundwater levels, respectively, when compared against baseline conditions (Fig. 5a).

Similarly, by 10 years in the middle section of the basin (Fig. 5b), a maximum of 5 m groundwater elevation difference was noted between the baseline and the 50% flow reduced scenario. The lesser reduction scenarios of 40, 30, 20 and 10% each yielded a groundwater elevation difference of 4, 3, 2 and 1 m, respectively, when compared with the baseline.

When analyzing the downstream section of the basin (Fig. 5c), by 10 years, the 50% scenario yielded an increase of 2 m in groundwater elevation, when compared with the baseline. The lesser reduction scenarios yielded lesser increase, with the 40, 30, 20 and 10% scenarios yielding a groundwater elevation difference of 1.8, 1.3, 1 and 0.5 m, respectively, when compared with the baseline.

Mapping of flood inundation extent under current flows

This section investigates the return period of different annual peak discharges at the Ramganga outlet, and mapping of flood inundation extent using HEC-RAS for each return period under baseline and reduced basin outflow scenarios from 10 to 50%. The return period of annual peak discharges at the Ramganga outlet for the period 1996–2010 was established using the Weibull plotting method on annual peak discharges generated by the SWAT model. The generated plots of discharge versus return period are shown in Fig. 6.

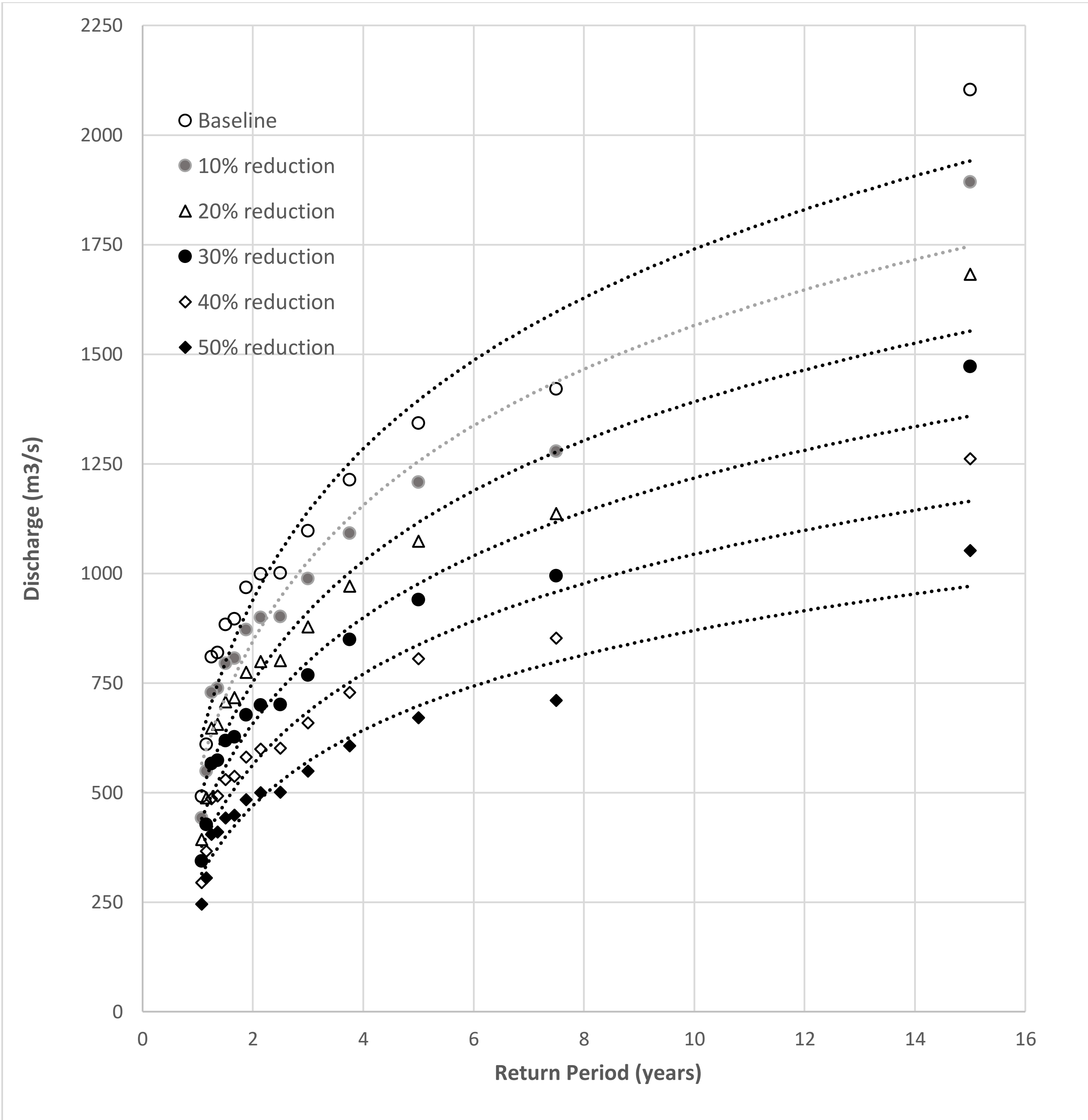


Figure 6. The discharge vs. flood return period graphs for the Ramganga outlet under baseline and reduced flow scenarios

The years which showed return period discharges of 2, 5 and 15 years were identified from the above plot and HEC-RAS model simulations were carried out for those particular events to map inundation extent under each return period flood. The actual inundated extent and the water level at the outlet of the Ramganga basin under each return period flood was also calculated. This exercise was repeated under reduced basin outflow scenarios of 10–50% and results are shown in Table 3. The inundated extent under a 15-year return period flood for the baseline condition is shown in Fig. 7.

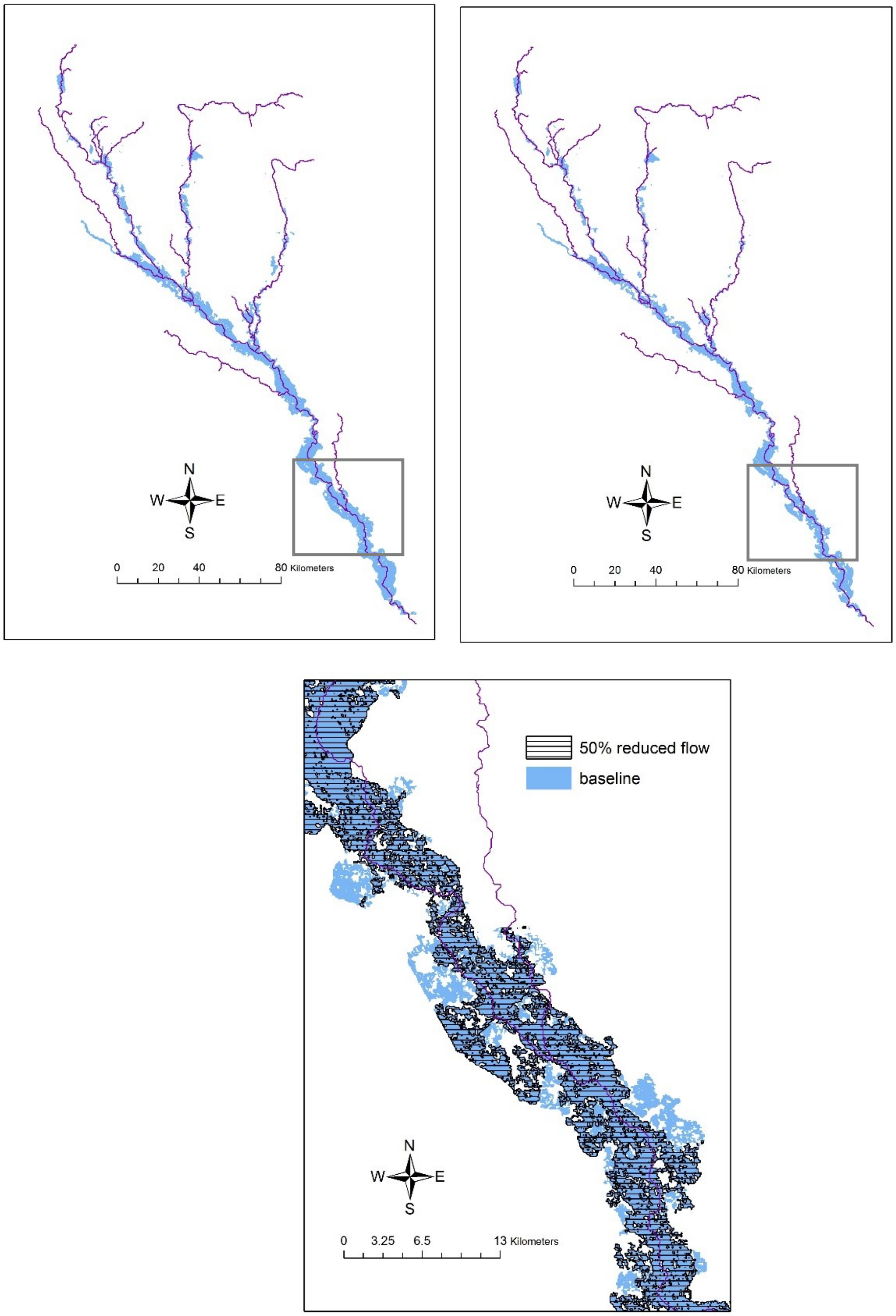


Figure 7. Areas inundated in a 15-year return period flood under the baseline basin outflow scenario (*top-left*) and under a 50% reduced basin outflow scenario (*top-right*) with an overlay of the two extents near the outlet of the Ramganga basin (*bottom*)

Table 3. Inundated extent under different return period floods under baseline (current) basin outflow and reduced basin outflow scenarios

Return Period (years)	Area (thousand Ha)					
	Baseline	10% reduced flow	20% reduced flow	30% reduced flow	40% reduced flow	50% reduced flow
2	108	103	97	93	87	80
5	118	112	104	100	93	86
15	141	135	127	122	115	107

It can be seen that basin outflow reductions result in lowering the magnitude (i.e., return period, inundated area) of current floods. For example, a 20% reduction in peak flows at the outlet of the basin converts a 15-year flood peak to an approximately 8-year flood peak, a 5-year peak to 3 years and a 2-year peak to just above a year. A 20% reduction in basin outflow generally results in a 10% reduction in the inundated area in all return periods. As far as water level changes at the outlet are concerned, the highest reduction in water level for the 20% flow reduction scenario is shown for a 15-year return period flood (0.45 m). Hence, distributed upstream MAR practices can be effective in reducing damages due to larger return period floods, and increasing the groundwater levels.

Water balance results

The overall basin water balance can be discussed in terms of the key inflow (total recharge and river leakage) and outflow (total discharge and baseflow) parameters. The runoff reduction scenarios indicated that, in comparison to the baseline conditions, the total annual average groundwater recharge increased by 11, 22, 34, 45 and 56% for the 10, 20, 30, 40 and 50% scenarios, respectively (Table 4). Due to enhanced groundwater recharge activities, the annual average water flux from the river to the groundwater decreased by 14, 21, 29, 35 and 41% for the 10, 20, 30, 40 and 50% scenarios, respectively (when compared against the baseline conditions). In terms of outflow, under the current water demand scenario, the annual average groundwater flux from the aquifer to the river (baseflow) increased due to higher levels of groundwater. The annual average baseflow contribution from aquifer increased by 25, 39, 57, 75 and 95% for the 10, 20, 30, 40 and 50% sub-scenarios, respectively (Table 4). There was negligible reduction in the discharge from the aquifer, as the current water demands were kept same in the scenarios. Therefore, from a water balance perspective, there has been an increase of water flux into the aquifers from MAR, which has resulted in an increase in baseflow contribution from the aquifer.

The results from this semi-coupled modeling study indicate that distributed MAR structures across the Ramganga basin can result in a reduction of downstream flood discharge (during monsoon months) and an increase in groundwater levels. Moreover, the improved groundwater levels can cater to the higher water demands during the dry season.

Table 4. Annual average change in aquifer inflow and outflow components between baseline and reduced basin outflow scenarios in the Ramganga basin

Scenario	Baseline	10%	20%	30%	40%	50%
Aquifer Recharge						
Annual average absolute volume (km^3)	3.78	4.2	4.63	5.06	5.49	5.92
Change from baseline (%)	-	11	22	34	45	56
River Leakage						
Annual average absolute volume (km^3)	0.62	0.54	0.49	0.44	0.4	0.36
Change from baseline (%)	-	-13 *	-21	-29	-35	-41
Aquifer Discharge						
Annual average absolute volume (km^3)	6.37	6.32	6.27	6.22	6.17	6.12
Change from baseline (%)	-	-1	-2	-2	-3	-4
Baseflow						
Annual average absolute volume (km^3)	0.44	0.55	0.61	0.69	0.77	0.86
Change from baseline (%)	-	25	39	57	75	95

** in published paper, river leakage % change for 10% scenario was erroneously written as -1 instead of -13*

Conclusions

This study has applied a semi-coupled framework in the Ramganga basin to test scenarios that can bridge the extremes in basin-wide water supply and demand. Initially, a hydrological model (SWAT), groundwater model (MODFLOW) and flood inundation model (HEC-RAS) were used to understand the baseline hydrologic regime. Then, a suite of MAR scenarios were tested relative to baseline conditions. This involves the introduction of distributed MAR structures across the basin that leads to the reduction of basin outflow and an improvement in groundwater levels. Results indicated that the groundwater levels gradually improved after a 5-year period, resulting in a reversal of the groundwater depletion trend. In addition, such scenarios also resulted in a reduction in basin net outflow, thus leading to a likely reduction in flood damage. Results further indicate that peak flow reductions result in lowering the magnitude (i.e., return period, inundated area) of current floods. For example, a 20% reduction in flows at the outlet of the basin converts a 15-year flood peak to an approximately 8-year flood peak, a 5-year peak to 3 years and a 2-year peak to just above a year. Therefore, MAR activities, if implemented at scale in the Ramganga basin, can be effective in reducing river discharge, flood magnitudes and associated flood damages, as well as increase overall groundwater levels.

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