Interactive comment on "Reviving the "Ganges Water Machine": where and how much?" by L. Muthuwatta et al. (Anonymous Referee #1)

Comments:

1.What's the difference between gw recharge and net gw recharge? Sentence seems inconsistent (increasing recharge by 35% increases recharge by 12%).

This has been corrected in the manuscript.

2. Reduced
This has been corrected in the manuscript.

3. How do you know that?
Additional text is added to clarify the issue.

Additionally, pumping groundwater during dry season may reduce water pumped from the river directly.

4 And replaced by gw pumping? It's not clear that Khan et al support the statement that gw pumping will replace sw pumping and that that will increase baseflow.

Following description is added to the manuscript.

Khan et al (2014) suggest that not withdrawing water from the river during dry season (which makes up to 50% of the 28 Bm^3 of the annual water withdrawal) in state of Uttar Pradesh (UP) will increase flow by 25% in the Ganges at the UP-Bihar boundary. But the authors do not mention how to meet the unmet demand. The reduced surface water pumped can be replaced with increased groundwater pumping (augmented with artificial recharge during the previous wet period).

5. Investigation of
This has been corrected in the manuscript

6. Increased?
This has been corrected in the manuscript

7. You mean that homogeneity in land use and hydrological response is assumed? I wouldn't say it leverages similarity.
This has been corrected in the manuscript.

8. But any threshold size would include all tributaries in the model domain. I still don't understand the rationale for area threshold selection.

The algorithm used in SWAT for the delineation of sub-basins and river network uses flow accumulation and flow direction grids calculated from digital elevation model. Final delineation requires the "area threshold" to define number of cells to calculate the contributing area for each stream. The smaller the threshold, the more detailed is the river network with finer sub-basin. A very small threshold will create too many sub-basins and increase computation time substantially. There needs to be a balance between river network details and computation time. In this study we have used 3,000 ha as the minimum area threshold based on trial and error method in order to include all major tributaries while also keeping computation time within practical range.

9. Where's Harding bridge? What's the drainage area? Show in figure 1.

Location of the Harding Bridge is added to Figure 1.

10. Describe in one sentence why some subbasins (eg 8) don't have any swat hrus.

Following text is added to the manuscript

Figure 1 shows the 22 major sub-basins (Table 3) in the GRB as defined by the Central Water Commission (CWC) of India, which is the main government agency responsible for water resources development and management in the Ganges River Basin. Since the focus of this study is to estimate water availability in the sub-basins within India, Nepal is considered as one region. The smaller spatial units inside those 22 sub-basins and Nepal are termed 'catchments' and were developed using SWAT interface, as discussed above. The catchments do not completely match with some of the sub-basins due to limitation in SWAT with processing coastal basins.

11. Isn't the rmse most important since you're estimating volumes?

RMSE is added to the table 2.

12. Some of these aren't listed in table 3, so we don't know where the are. Please put the gage locations on figure 1.

Gauge locations are added to the Figure 1.

13. Please add a sparse river network so we cansee how the subbasins are connected.

River network is added to the Figure 1.

14. Flows

This has been corrected in the manuscript

15. Grammar

This has been corrected in the manuscript

16. Determines

This has been corrected in the manuscript

17. In just the ramganga? Whole Ganges?
Linear regression? How many years? How did you identify the date that had the peak flood area?

18. What was done in amarnath? The flood mapping of ramganga? Clarify.
To address these two comments, following text is added to the manuscript

The study conducted by Amarnath et al (2012) developed a data set that used the algorithm based on number of water and vegetation indices (Land Surface Water Index (LSWI), Enhanced Vegetation Index (EVI), Normalized Difference Vegetation Index (NDVI) and Normalized Difference Snow Index (NDSI)) on the MODIS 8-day surface reflectance bands to estimate spatial extent and the temporal patterns of flood inundated area (Amarnath et al, 2012). This data set was used to acquire maximum flood inundated area for Ramganga. The effect of surface runoff on maximum flood-inundated area in Ram Ganga was investigated by relating annual values of maximum flood inundated areas with the river flow using logarithmic regression from 2003 to 2010.

19. The hydrological terms are a bit mixed up here. But all ET had to infiltrate first. What's left after infiltration and ET (assuming no saturation overland or subsurface storm flow) is recharge, which becomes GW discharge and surface runoff during baseflow. Usually surface water runoff is defined as all streamflow, including storm flow and baseflow, which is what is leftover after Et and change in storage (Q = P -ET +/- change in storage). Or by surface runoff do you mean infiltration excess overland flow? I think that's what you mean, but then it's what is left after infiltration, not infiltration and ET.

This is clarified in the manuscript by adding following description

The spatial and temporal distribution of the annual surface runoff is analyzed to determine the water availability in different sub-basins. River flow includes surface runoff and baseflow from groundwater, which can be captured by diversion or from dams. Surface runoff is calculated in SWAT using SCS curve number method (SCS, 1972). In the standard hydrological definitions, it is the direct runoff which is part of the precipitation that is left after infiltration, and can be captured for MAR before it reaches the stream. It. Therefore, only the surface runoff portion was considered for augmenting SSS. Figure 2 shows the simulated catchment-scale mean annual surface runoff.

20. And "surface runoff"?

This has been corrected in the manuscript

21. From the ungaged subbasin?

All the sub-basins other than what we have calibrated are ungauged. Ww are not sure the reviewer is aiming for that.

23. Why do some subbasins have no values (eg Nepal).

We agree with the reviewer and the estimated mean annual out flow from the Nepal is added to Figure 4.

24. Kharif? Or third summer crop (April-June)? Define the seasons by months.

Why is irrigated area so much smaller in hot than rabi? Without knowing whether this is kharif season or not makes it hard to tell. If it's a third crop, then what is kharif irrigated area? And is it assumed to be maximum and not changed in the scenarios?

25. dry season

26. Same as hot season? But rabi is also a period of low rainfall.

This issue is clarified in the manuscript by defining the seasons by months (24,25,26).

27. But you also have to assume that the unmet demand is going to et, no? Just adjusting the CN would increase flow, but meeting unmet demand would decrease flow. If you're trying to simulate change in streamflow by enhancing recharge but not changing ET, that needs to be stated. But that is not the same as scenario 1 and 2, where unmet demand goes to et.

Clarification is added to the manuscript

Since our goal for running these scenarios is to show the feasibility of storing groundwater for future dry season water demand, we did not considered ground water pumping in the dry season. Volumes of groundwater recharge and the changes of base flow under these scenarios were estimated.

28. indicates
This has been corrected in the manuscript

29. 50% of what?
This issue is clarified in the manuscript by re writing the text.

This shows that increasing groundwater recharge by 35% would help to increase SSS, which is sufficient to meet 50% and 33% of the unmet agricultural water demand under the two scenarios respectively (Table 4).

30. Even after pumping of gw to meet unmet demand?
This has been clarified in the manuscript

31. Each year
This has been corrected in the manuscript

32. Taken from another reference?
Reference is added to the manuscript.

The relationship between the simulated maximum monthly river flow and the maximum flood inundated areas in Ramganga is shown in Figure 6. Horizontal axis represents simulated maximum monthly river flow during each year from 2003 to 2010 at the Ramganga outlet. Vertical axis shows the maximum flood inundation areas estimated based on the satellite images in the corresponding year (Amarnath et al., 2012).

33. What's the impact on annual discharge? It should large and equal to unmet demand.

34. Maximum monthly

This has been corrected in the manuscript

35. On monthly maximum? Annual?

This has been corrected in the manuscript

36. Grammar

This has been corrected in the manuscript

Therefore, to understand the potential impacts of SSS on flooding in the GRB, further research is required to investigate the effect of SSS on control of floods in the downstream areas.

37. Grammar

This has been corrected in the manuscript

Creating additional SSS beyond the current levels in the Ganges River Basin can simultaneously enhance water supply and control downstream floods.

38. Total surface runoff? Elsewhere in the paper total runoff is surface plus gw.

This has been corrected in the manuscript

39. Is that a big number or a small number? Compared to what?

This is clarified in the manuscript

40. I don't think that's a meaningful comparison. High inflow compared with local rain is true for any large river.

Text is removed from the manuscript

41. Before meeting unmet demand through irrigation....
This has been corrected in the manuscript

42. So, is et from unmet demand simulated by you or not?

This is clarified in one of the answers given above.

Interactive comment on "Reviving the "Ganges Water Machine": where and how much?" by L. Muthuwatta et al. (Anonymous Referee #3)

Major comment:

The authors have done a very good job revising this study. The new figures really help expand the novelty of the analysis and the findings. With that there are only some minor editorial comments to consider and one major comment to address. For the major comment, I leave it to the discretion of the editor for the final decision since one could consider the comment stylistic.

The lack of a discussion section still bothers me. From a research point of view, this come across as weak since it means the feasibility and impact of the results are not considered in any broader context. Personally, such a section is needed to integrate the author's responses to my (and the other reviewer) comments from the previous iteration of review. That would greatly improve the readability and presentation of the study. Traversing from results to conclusion makes the manuscript come across more as an engineering report rather than a full scientific study. I leave it to the editor to decide how this can be handled.

Answer: Separate discussion section is added to the manuscript.

Minor comments

1. Change "can" to "could"
This has been corrected in the manuscript

2. Change "create" to "created"

This has been corrected in the manuscript

3. Change “period” to “periods”
This has been corrected in the manuscript

4. What is meant with “using aquifer”?
This is clarified in the manuscript.

Sadoff et al (2013) mentioned that using aquifers to store excess water is a national-level alternative for upstream water storage and has a potential to argument dry season flows (although it requires other factors such as appropriate energy-pricing and policy environment in conjunction with a well-managed surface water system).

5. The sentence beginning with “Additionally,” does not make sense.
This sentence is removed from the manuscript

6. Change to “the state”
This has been corrected in the manuscript

7. It would be fair to change this to “for a complete investigation (including field pilot tests) into the plausibility for a well-designed”
This has been corrected in the manuscript

8. Change to “Nash-Sutcliffe efficiency (NS)
This has been corrected in the manuscript

9. Change “are” to “were”
This has been corrected in the manuscript

10. Change “are” to “were”. Double check for verb tense consistency throughout.
This has been corrected in the manuscript

11. Change to “with the typical”
This has been corrected in the manuscript

12. Change to “The area”
This has been corrected in the manuscript

13. Change to “the sub-surface”

Reviving the ‘Ganges Water Machine’: Where and how much?

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Abstract

Surface runoff generated in the monsoon months in the upstream parts of the Ganges River Basin (GRB) contributes substantially to downstream floods, while water shortages in the dry months affect agricultural production in the basin. This paper examines the potential for subsurface storage (SSS) in the Ganges Basin to mitigate floods in the downstream areas and increase the availability of water during drier months. The Soil and Water Assessment Tool (SWAT) is used to estimate “sub-basin” water availability. The water availability estimated is then compared with the sub-basin-wise un-met water demand for agriculture. Hydrological analysis reveals that there is sufficient water to meet the un-met water demand in the sub-basin provided that it is possible to capture the surface runoff in sub-surface storage during the wet season. To examine the impacts of groundwater recharge on flood inundation and flows in the dry season, two groundwater recharge scenarios are tested in the Ramganga sub-basin. Increasing groundwater recharge by 35% and 65% of the current level would increase the volume of water in aquifer by 1.25 Bm^3 and 1.44 Bm^3 respectively. Some of the groundwater recharge is returned to stream as base flow and has the potential to increase dry-season river flows. Augmenting SSS reduces the peak flow and flood-inundated areas in Ramganga (by up to 8% for 65% scenario compared to baseline), indicating the effectiveness of SSS on reducing inundated areas under floods in the sub-basin. However, this may not be sufficient to effectively control the flood in the downstream areas of GRB, such as in the state of Bihar, prone to floods, that receives total flow of 277Bm^3 from upstream sub-basins.

Key words: Ganges, Hydrological modeling, SWAT, Subsurface storage, Surface runoff, Floods.

Introduction

Matching water demand with supply in river basins with monsoonal climate is a major challenge. The monsoon-driven seasonal hydrology in India is often associated with floods and droughts, which affects the most vulnerable people of society (women and children, the poor and other disadvantaged social groups), and causes damage to crops and infrastructure. In these basins, upstream storage is generally the preferred solution to buffer the variability of flow and reduce floods downstream (Khan et al., 2014). Traditionally, dams are the major surface water storage structures. However, the construction of large dams requires huge investments, displaces people, submerges forests, and some of the water is lost to non-beneficial evaporation (Pavelic et al., 2012). In contrast, underground aquifers are efficient water reservoirs with minimum evaporative losses, no displacement of people or submergence of land (Bouwer 2000; Dillon 2005; Ghayoumian et al., 2007).

For centuries, the utilization of water resources in the Ganges River Basin has been severely hampered by substantial seasonal variation in river flows. In the basin, the main source of water is the (southwest) monsoon rainfall, and also the snowmelt and ice melt in the Himalaya during the summer season (Sharma and de Condappa, 2013). Out of the 1,170 billion cubic meters (Bm^3) of water entering the basin, around 500 Bm^3 becomes river flow while the remainder is returned to the atmosphere through evapotranspiration (SAWI, 2013). The monsoon (between June and September) contributes to about 80% of total annual rainfall, and about 80% of the annual river flow (Revelle and Lakshminarayana, 1975). The rainfall during the rest of the year is low and the river flows, generated mainly through recharged groundwater and snowmelt, are barely sufficient to satisfy the water needs of all the sectors (Huda and Shamsul, 2001). For instance, the estimated average annual flow (1990 to 2008) at the Harding Bridge in Bangladesh (just downstream of the Indian border, with drainage area of 944,000 Km^2) was about 340 Bm^3 and ranged from 197 Bm^3 to 486 Bm^3, whereas flow in the dry season (October to May), at the same location, varied from 43 Bm^3 to 63 Bm^3.

Extensive flooding in the Ganges River Basin, especially in the downstream areas, occurs annually (Mishra 1997). The major causes of floods in the downstream areas are the shallow groundwater table and high monsoonal rainfall in these areas, and the large surface runoff generated in the upstream sub-basins. Previous studies (Revelle and Lakshminarayana, 1975; Sadoff et al., 2013) indicated that, due to the limitation of the construction of large surface reservoirs, recharging groundwater beyond the natural level is the best way to control floods downstream. Subsurface storage (SSS) also allows meeting water requirements during the dry months. Popular belief is that having large dams is the only option to meet the basin's water storage needs (Onta, 2001). However, contrary to that, the Ganges strategic basin assessment conducted by the World Bank (2012) found that the sustainable use of the basin's vast groundwater aquifers can store far greater volumes of water compared to the potential of man-made storage in the basin, which is about 130-145 Bm^3 (Sadoff et al., 2013). For instance, the mean annual replenishable groundwater in the Ganges basin is about 202.5 Bm^3 (Ministry of water resources, 2014). Another study found that the estimated storage available in the shallow alluvial aquifers of eastern Uttar Pradesh and Bihar, which could be utilized in the dry season and naturally recharged in the wet season, is 30-50 Bm^3 (SMEC, 2009).

From a purely biophysical perspective, four conditions are necessary to develop sustainable SSS solutions (that involve groundwater recharge beyond the natural levels) to tackle water scarcity and flood damage in the basin:

1. Existence of adequate un-met demand (e.g., for agriculture and other uses) to deplete the water pumped from the aquifers in a basin/sub-basin.
2. Existence of adequate flows for capture during the monsoon season.
3. Existence of extra underground space, which can be created by pumping and depleting groundwater before the onset of the monsoon.
4. Ability to actually capture the excess monsoon surface runoff to recharge that additional space created - naturally (through surface water and groundwater interactions) or artificially (through managed aquifer recharge (MAR)).

Amarasinghe et al. (in press) examined the first condition above and estimated un-met demand throughout the basin under two scenarios of irrigation expansion. The main objective of this paper is to examine the second condition above, i.e., assess the potential availability of runoff and the impact of managed groundwater recharge on the river flow. A hydrological model – Soil and Water Assessment Tool (SWAT) was used to conduct a hydrological analysis of the sub-basins of the Ganges River Basin. This study does not determine whether there is sufficient aquifer storage available to hold the excess runoff, as this requires detailed groundwater aquifer modeling in sub-basins of GRB. In fact, a comprehensive assessment of the groundwater system in the Ganges is beyond the scope of this work. To the best of the authors' knowledge, no such work has been done for whole of GRB although this could be done by using the Gravity Recovery and Climate Experiment (GRACE) satellite (Swenson and Wahar, 2006; Morrow et al, 2012, Rodell et al., 2009). Rodell et al., 2009 used GRACE satellite data to estimate the mean rate of groundwater depletion over the Indian states of Rajasthan, Panjab and Haryana as 17.7 ± 4.5 km3/year. Chinnasamy (forthcoming) estimated that groundwater depletion rate over Ramganga sub-basin located in the Northwestern part of the GRB as 1.6 km3/year, and concluded that, the depleted aquifer volume can be used to store upto 76% of the rainfall in the sub-basin. Khan et al. (2014) showed that the subsurface storage created in Uttar Pradesh by pumping groundwater during dry periods can accommodate up to 37% of the yearly average monsoon flow.

Recharging of surface runoff to the groundwater aquifer during the monsoon season may have minimal effect to the downstream flow during the monsoon season. In fact, increased groundwater recharge may increase the contribution of groundwater to the river flow. However, the excess pumping of water from the aquifer can affect the dry season flows. Sadoff et al (2013) mentioned that using aquifers to store excess water is a national-level alternative for upstream water storage and has a potential to argument dry season flows (although it requires other factors such as appropriate energy-pricing and policy environment in conjunction with a well-managed surface water system). Khan et al (2014) suggest that not withdrawing water from the river during dry season (which makes up to 50% of the 28 Bm^3 of the annual water withdrawal) in state of Uttar Pradesh (UP) will increase flow by 25% in the Ganges at the UP-Bihar boundary. But the authors do not mention how to meet the unmet demand. The reduced surface water pumped can be replaced with increased groundwater pumping (augmented with artificial recharge during the previous wet period). Investigation of the effect of increased groundwater recharge and abstraction on downstream low flows requires conjunctive modeling that couples both groundwater and surface water models. In this study SWAT (which has a simplified groundwater model linked to surface water model) is used to demonstrate this in the Ramganga sub-basin located in the northwestern part of the GRB. Although this study is a theoretical exercise, it provides a scientific justification for a complete investigation (including field pilot tests) into the plausibility for a well-designed managed aquifer recharge program to enhance the sub-surface storage in GRB.

Methodology

The Model

Many models have been developed (e.g., Eastham et al., 2010; Gosain et al., 2011; World Bank, 2012) to study water issues in the Ganges River Basin (Johnston and Smakhtin, 2014). However, they are not available to the public. To overcome this restriction and provide the research community with a working hydrological model for the Ganges River Basin, the International Water Management Institute (IWMI) has developed a publicly available hydrological model for the basin (Muthuwatta et al., 2014) using the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998). The model set up files can be downloaded from the website http://waterdata.iwmi.org/model_inventory.php, and used in further applications and scenario analyses in a variety of projects.

SWAT is a widely used, semi-distributed conceptual hydrological model developed by the Agricultural Research Service of the United States Department of Agriculture (USDA) over the last 30 years, and is available free of charge as a public domain model (Arnold et al.,1998; Gassman et al., 2007; Sood et al., 2013). The model has been previously being used for number of studies for different watershed scales (e.g. Muttiah and Wurbs, 2002; Ringler et al, 2010; Singh & Gosain, 2011, Sood et al, 2013). The hydrological ability of the model to capture real world situations is extensively discussed in these articles. Broadly, the SWAT input data can be grouped into five categories: topography or terrain, land use, soil, land use management and climate (Neitsch et al., 2002). SWAT possesses adequate representation of processes governing hydrology and is particularly suitable for application in large river basins. In SWAT, a river basin is subdivided into a number of catchments, so that each catchment has at least one representative stream. Based on unique combinations of soil, land use and slope, the catchments were further divided into hydrological response units (HRUs), which are the fundamental units of calculation. Subdividing the watershed into areas having unique land use, soil and slope combinations enables the model to reflect differences in evapotranspiration and other hydrologic conditions. HRUs allow for a modeling efficiency by lumping pixels with similar land use, soil and slope properties.

SWAT simulates the local water balance of the catchment through four storage volumes - snow, soil profile, shallow aquifer and deep aquifer – based on the soil water balance (Equation 1):

$$SW_t = SW_0 + \sum_{\mathrm{t=1}}^{\mathrm{t}} (R_t - SR_t - ET_t - P_t - G_t) \qquad (1)$$

Where: SW_t is the soil water content minus the wilting-point water content at time *t*, and R_t, SR_t, ET_t, P_t, and G_t are the daily amounts (in mm) of rainfall, runoff, evapotranspiration, percolation and groundwater flow, respectively, at time *t*. SW_0 is the initial soil water content. The simulated processes include surface runoff, infiltration, evaporation, transpiration, lateral flow, and percolation to shallow and deep aquifers.

The Data and Model Setup

The model used in this study was set up using the datasets shown in Table 1. The Ganges River Basin was delineated using 3,000 ha as the minimum area threshold and has resulted in 1,684 catchments (Figure

1). The area threshold was selected by trial and error in an attempt to represent major tributaries in GRB, while also keeping the SWAT sub-basins to the minimum.

The model was initially developed to study river flow entering Bangladesh. Therefore, the spatial domain of the SWAT model developed for the Ganges does not entirely cover the areas that belong to West Bengal and Bangladesh. However, this does not affect the current study, as its focus is to assess water availability in the upstream sub-basins of the Ganges River Basin.

Table 1: An overview of the main datasets used in this study.

Category	Data	Data source
Topography	Digital elevation model (DEM)	Shuttle Radar Topography Mission (SRTM)
Land use	Land-use map	IWMI database – Satellite-based land-use map
Soils	Digital map of soils and soil Properties	FAO soil map of the world, 1995
Climate	Rainfall, temperature, relative humidity, sunshine hours, wind speed	Meteorological organization in Bangladesh, Re-analysis data, India Meteorological Department
Hydrology	River discharge	IWMI Water Data Portal

Figure 1 shows the 22 major sub-basins (Table 3) in the GRB as defined by the Central Water Commission (CWC) of India, which is the main government agency responsible for water resources development and management in the Ganges River Basin. Since the focus of this study is to estimate water availability in the sub-basins within India, Nepal is considered as one region. The smaller spatial units inside those 22 sub-basins and Nepal are termed 'catchments' and were developed using SWAT interface, as discussed above. The catchments do not completely match with some of the sub-basins due to limitation in SWAT with processing coastal basins.

The model was initially calibrated and validated for the monthly discharge data collated at the Harding Bridge. The calibration period was selected from 1981 to 1990 and the validation period was selected as 1991–2000. The performance indicators, Nash-Sutcliffe efficiency (NS) and coefficient of determination (R^2) were 0.69 and 0.73, respectively, for the calibration period and indicate reasonable agreement between observed and simulated river flow time series. For the validation period, NS and R^2 were 0.75 and 0.81. Additionally the model simulations were compared with the observed flow data at another seven locations, for which the observed data were available. Table 2 presents the model performance indicators for these seven locations. The performance indicators show reasonable values. Further, simulated water balance components seem to be comparable to the results of the other similar studies (e.g. Gosain and Sirinivasan, 2011). For more details on the model setup, including calibration and validation, please refer to Muthuwatta et al., 2014.

Table 2: Model performance indicators for seven locations in GRB.

Gauge	River	Latitude	Longitude	Period	R^2	NS	RMSE (m^3/s)	Max. flow(m^3/s)
1	Baghmati	27.15	85.49	1981–2006	0.83	0.82	39.7	987.0
2	Karnali	28.96	81.12	1981–2006	0.79	0.61	224.4	2140.7
3	Seti	29.30	80.78	1986–2006	0.76	0.54	92.3	827.4
4	Arun	26.93	87.15	1986–2006	0.63	0.64	446.7	2300.6
5	Kali Gandaki	27.88	83.80	1996–2006	0.75	0.62	280.8	2420.6
6	Kali Gandaki	28.00	83.61	1987–1995	0.58	0.58	261.4	1081.9
7	Kali Gandaki	27.75	82.35	1984–2006	0.76	0.66	293.6	2710.4

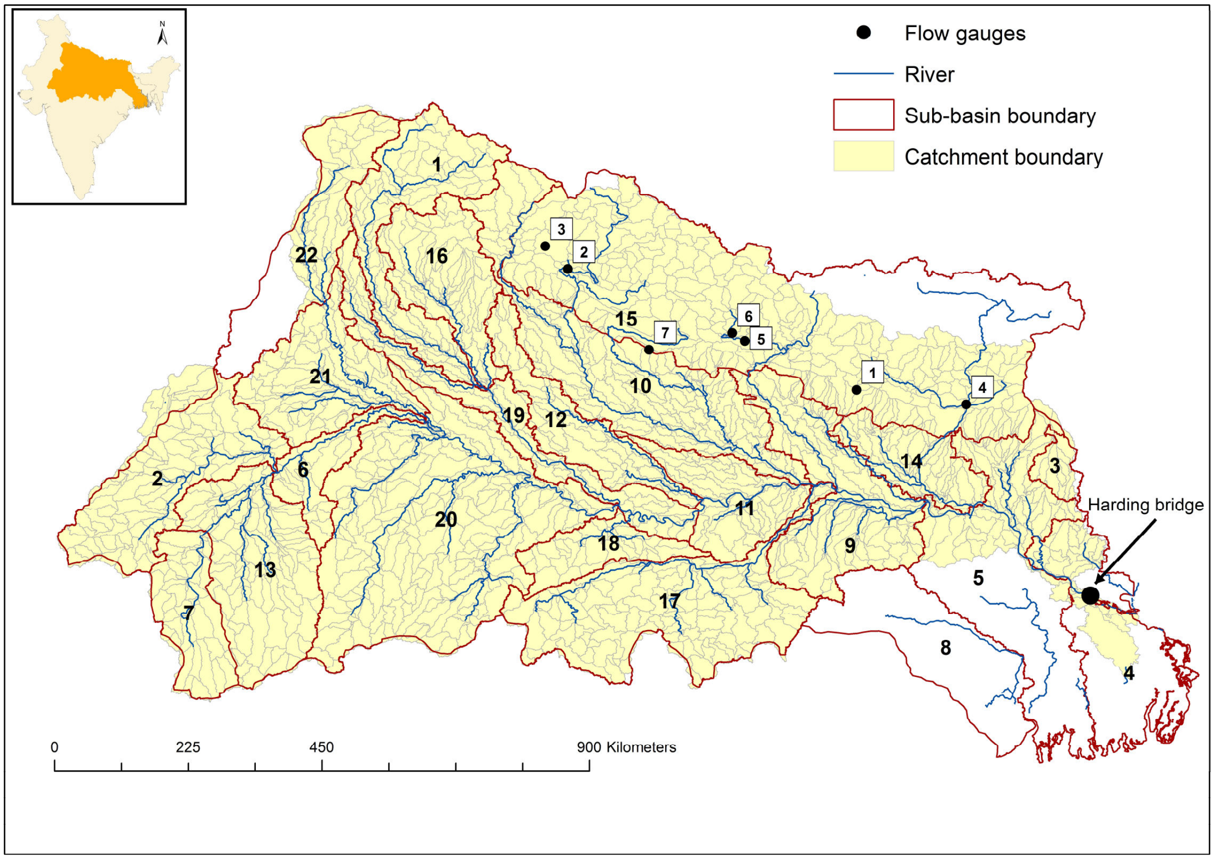

Figure 1: Sub-basins and catchments of the Ganges River Basin (Name of the sub-basins are given in Table 3).

Simulating Sub-basin Runoff

Annual time series of catchment-scale surface runoff from 1991 to 2010 were constructed by aggregating daily surface runoff simulated by SWAT. Next, using geographic information system (GIS) techniques, annual runoff time series were estimated for all sub-basins within the modeled area of the GRB. The study uses the hydrographs of the simulated runoff (SR) to estimate the 75% dependable runoff (SR_{75}). SR_{75} is an estimate of the runoff that can be expected in the basin, on average, every three out of 4 years, and is considered to be a reliable estimate of water availability for augmenting groundwater storage (Wang et al, 2014).

Simulating Groundwater recharge scenarios in Ramganga

To examine the effect of groundwater recharge on the hydrology such as monthly river flow, Ramganga sub-basin located in the northwestern part of the basin was selected. Ramganga sub-basin was selected because it is the first major upstream basin with the typical water resources management challenge of managing seasonal water variability and meeting water demand. The area of the Ramganga sub-basin is about 32,000 km^2 and it belongs to two administrative districts: Uttaranchal and Uttara Pradesh. The important tributaries that flow into Ramganga River are Kho, Gangan, Aril, Kosi, and Gorra. The surface water potential in the basin is about 18.6 Bm3. The population in the basin is about 20 million. The groundwater recharge was controlled in the SWAT model by changing the curve number (CN). CN determines the surface runoff in hydrological models. Reducing CN in the SWAT increases groundwater recharge.

Linking River Flow to Flood-inundated Areas

The study conducted by Amarnath et al (2012) developed a data set that used the algorithm based on number of water and vegetation indices (Land Surface Water Index (LSWI), Enhanced Vegetation Index (EVI), Normalized Difference Vegetation Index (NDVI) and Normalized Difference Snow Index (NDSI)) on the MODIS 8-day surface reflectance bands to estimate spatial extent and the temporal patterns of flood inundated area (Amarnath et al, 2012). This data set was used to acquire maximum flood inundated area for Ramganga. The effect of surface runoff on maximum flood-inundated area in Ram Ganga was investigated by relating annual values of maximum flood inundated areas with the river flow using logarithmic regression from 2003 to 2010.

Results

Surface Runoff of the Sub-basins

The spatial and temporal distribution of the annual surface runoff is analyzed to determine the water availability in different sub-basins. River flow includes surface runoff and baseflow from groundwater, which can be captured by diversion or from dams. Surface runoff is calculated in SWAT using SCS curve number method (SCS, 1972). In the standard hydrological definitions, it is the direct runoff which is part of the precipitation that is left after infiltration, and can be captured for MAR before it reaches the stream. It. Therefore, only the surface runoff portion was considered for augmenting SSS. Figure 2 shows the simulated catchment-scale mean annual surface runoff.

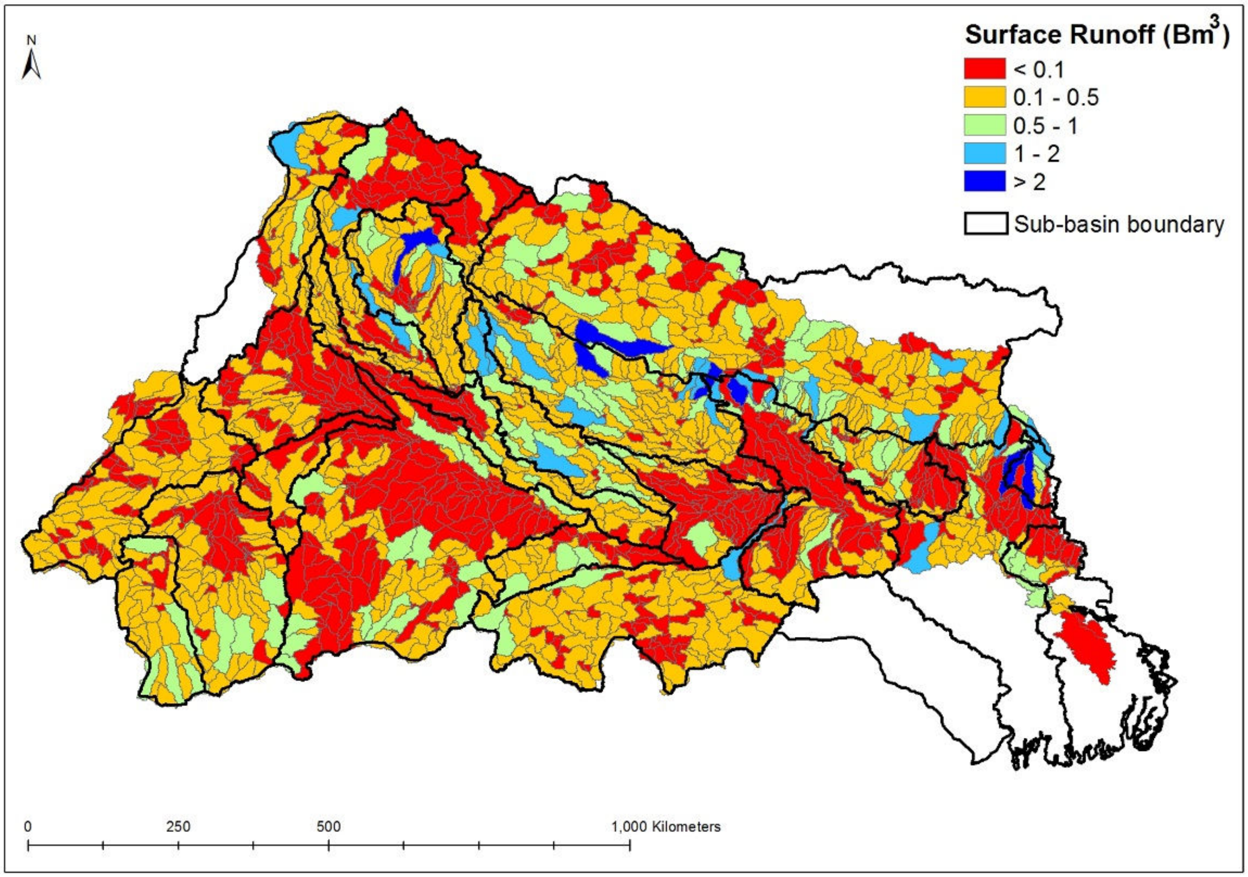

Figure 2: Mean annual surface runoff of the 1,684 sub-basins (1991-2010).

The surface runoff of catchments ranges from less than 0.1 Bm^3 to more than 2.0 Bm^3. The statistics of the estimated surface runoff for the sub-basins is given in Table 3.

Table 3: Surface runoff of the sub-basins.

Number	Sub-basin	Runoff (Bm^3)			Share of runoff as a percentage of total	
		Mean	Standard Deviation	SR_{75}	Wet months (June-October)	Dry months (November-May)
1	Above Ramganga confluence	10.02	5.04	5.48	81.2	18.8
2	Banas	9.89	7.11	3.51	93.8	6.2
3,4	Bangladesh	-		-	-	-
5	Bhagirathi and others	-		-	-	-
6	Chambal Lower	2.24	1.37	1.23	94.8	5.2
7	Chambal Upper	8.73	3.01	6.60	90.2	9.8
8	Damodar	-		-	-	-
9	Gandak and others	16.03	6.57	11.79	86.0	14.0
10	Ghaghara	35.56	17.55	23.34	84.0	16.0
11	Ghaghara confluence to Gomti confluence	4.72	2.07	3.32	88.3	11.7
12	Gomti	13.64	7.34	9.75	90.8	9.2
13	Kali Sindh and others up to the confluence with Parbati	15.48	6.64	10.51	80.9	19.1
14	Kosi	9.44	3.95	6.81	72.8	27.2
15	Nepal	63.17	11.59	54.44	88.0	12.0
16	Ramganga	15.56	7.79	10.11	82.6	17.4
17	Son	19.50	7.88	14.08	85.1	14.9
18	Tons	6.75	2.47	5.17	88.5	11.5
19	Upstream of Gomti confluence with Muzaffarnagar	9.38	4.77	5.70	87.8	12.2
20	Yamuna Lower	22.42	10.78	15.21	93.8	6.2
21	Yamuna Middle	4.81	3.70	2.14	78.7	21.3
22	Yamuna Upper	7.19	3.92	4.49	82.7	17.3

The estimates of mean annual surface runoff at sub-basin-scale range from 2.24 Bm^3 in Chambal Lower (6) to 63.17 Bm^3 in Nepal (15). Additionally, the high standard deviations in Table 4 indicate significant temporal variation within sub-basins. Further analysis shows that surface runoff in the wet months (June to October) is more than 80% of the annual surface runoff in most sub-basins (Table 4, last two columns). This intra- and inter-annual variability of the flows clearly indicates the need for storages to capture the excess surface runoff during the monsoon season, which could be a SSS. For this analysis, SR$_{75}$ was used to identify the sub-basins that are consistently producing higher volumes of surface runoff. Figure 3 shows the spatial distribution of SR$_{75}$ of sub-basins.

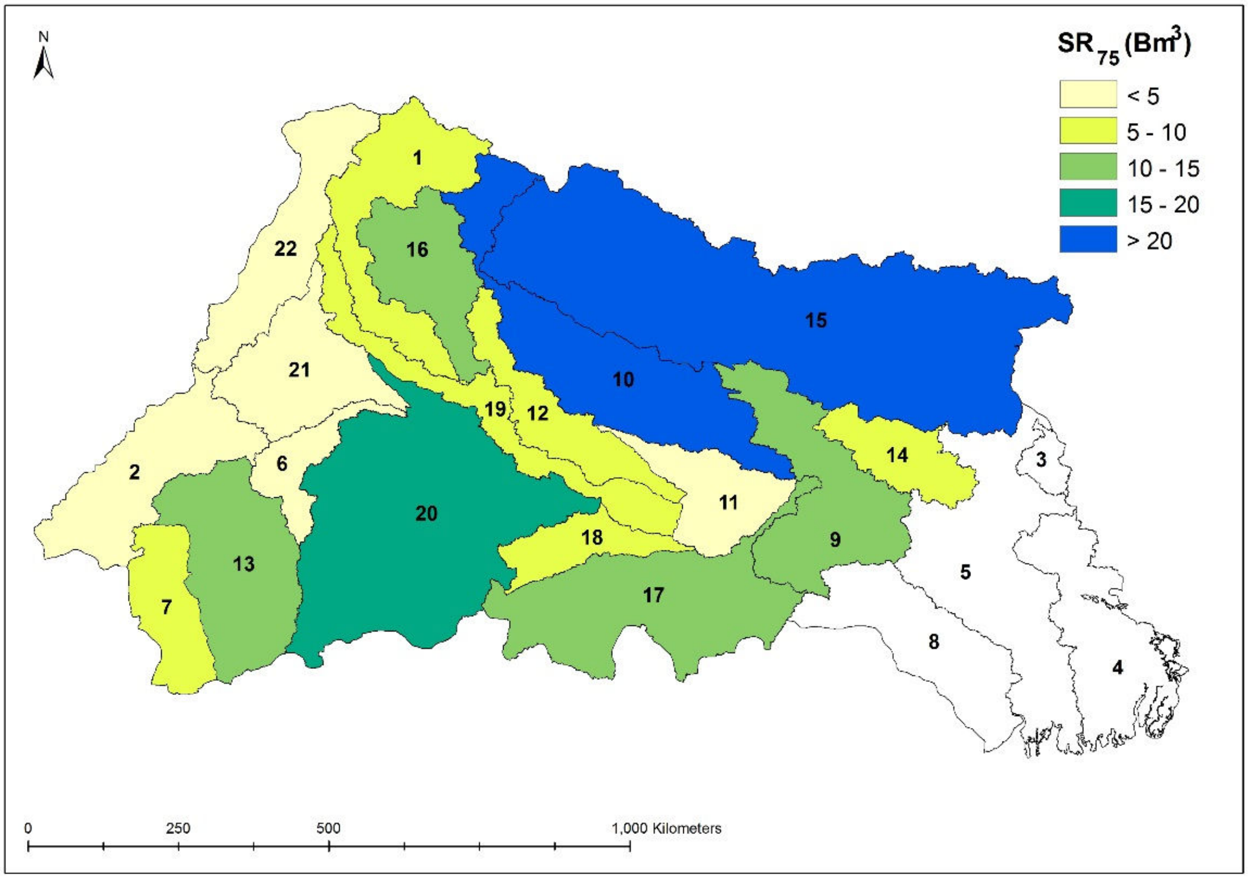

Figure 3: Sub-basin-scale annual dependable runoff (SR$_{75}$) in the Ganges River Basin (1991-2010).

Ghaghara (10) sub-basin and Nepal have, by far, the largest SR$_{75}$. The Kali Sindh (13), Ramganga (16), Son (17) and Yamuna Lower (20) sub-basins have more than 10 Bm^3 of SR$_{75}$. The Gandak (9) also produces higher surface runoff, but the sub-basin is located in the downstream area of the Ganges River Basin.

Because of the high monsoon runoff, the upstream sub-basins contribute substantially to flooding in the downstream areas of the Ganges River Basin.

Total discharge of the sub-basins.

The mean annual discharge from the upstream sub-basins from 2001 to 2010 was estimated and is presented in Figure 4.

Figure 4: Mean annual outflow (Bm^3) from the sub-basins in the Ganges River Basin (the numbers in black represent the mean annual outflow, and the numbers in brown on the yellow background represent numbers of the sub-basins).

The highest flow of 142.7 Bm^3 to Bihar in the downstream of the GRB is coming from upstream of the Gomati confluence to Muzaffarnagar (19), as it gets a large contribution from the Yamuna Lower (20) and Ramganga (16). The second highest flow (78.2 Bm^3) to Bihar is coming from the Ghaghara sub-basin (10) and it receives outflows from the western part of Nepal. The mean annual flow to Bihar from the various sub-basins in the Indian part of the Ganges River Basin is about 277±121 Bm^3, and the mean annual rainfall in Bihar is about 123±32 Bm^3. This indicates that the water volumes received from upstream flows are more than twofold the amount of rainfall in Bihar. Flow from Ghaghara and Yamuna Lower sub-basins is approximately 30% of the total inflow from the upstream Ganges River Basin to Bihar. The contributions from Son, Kali Sindh and Ramganga are 17%, 10% and 7%, respectively. The estimated discharges at the sub-basin outlets, as shown in Figure 4, include the contributions from upstream sub-basins and also the contribution of groundwater and surface runoff to the river flow. Therefore, the values presented in Figure 4 are significantly higher compared to the surface values presented in Figure 3.

Un-met Water Demand for Agriculture

Amarasinghe et al. (in press) estimated the un-met agricultural water demand. Two scenarios were considered in the analysis (Table 4).

Scenario 1: Provide irrigation to the total irrigable area, i.e., increase irrigated area in the Rabi season (November to March) from 26 million hectare (Mha) (current irrigated area in this season) to 30 Mha (irrigable area), and in the hot-weather season (April to June) from 3 Mha (current irrigated area in this season) to 30 Mha (irrigable area), respectively.

Scenario 2: Provide irrigation to the total cropped area. At present, not all cropped area is equipped for irrigation. i.e., irrigable area (30 Mha) is less than the cropped area (35 Mha). Therefore, the Scenario B is to increase irrigable area and to increase irrigated area from 26 to 35 Mha in the Rabi season and from 3 to 35 Mha in the hot-weather season respectively.

As of now, all the sub-basins in the Ganges River Basin have substantial un-met water demand for agriculture in the dry period (November to May). Therefore, capturing a substantial portion of the surface runoff during the monsoon months can help close the gap between current supply of water and demand in the dry months, thus increasing agricultural productivity in these sub-basins. Table 4 presents the sub-basin-wise un-met demand and the percentage of dependable runoff required to close the un-met demand.

Table 4: Sub-basin-wise un-met agricultural water demand and the percentage of surface runoff required to close the un-met demand.

Sub-basin	Unmet demand (Bm^3)		Percentage of the SR$_{75}$ required to close the un-met demand	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Above Ramganga confluence	1.71	2.44	31.2	44.5
Banas	1.21	4.09	34.5	116.6
Bangladesh	-	-	-	-
Bhagirathi and others	4.61	15.12	39.1	128.4
Chambal Lower	0.83	1.39	67.7	113.4
Chambal Upper	2.57	5.15	38.9	78.0
Damodar	-	-	-	-
Gandak and others	5.17	7.17	43.9	60.8
Ghaghara	5.11	7.49	21.9	32.1
Ghaghara confluence to Gomti confluence	3.37	2.89	101.5	87.1
Gomti	2.63	2.83	27.0	29.0
Kali Sindh and others up to confluence with Parbati	3.9	7.14	37.1	67.9
Kosi	1.03	2.39	15.1	35.1
Nepal	-	-	-	-
Ramganga	2.48	3.28	24.5	32.4
Son	1.92	11.82	13.6	83.9
Tons	0.68	2.34	13.2	45.3

Upstream of Gomti confluence to Muzaffarnagar	2.93	3.9	51.4	68.5
Yamuna Lower	7.75	18.67	51.0	122.8
Yamuna Middle	3.41	4.72	159.1	220.2
Yamuna Upper	3.72	5.58	82.8	124.2

In the sub-basins, the total un-met demands are 55.03 Bm^3 and 108.4 Bm^3 under scenarios 1 and 2, respectively. The values presented in Table 4 show that, for some sub-basins, annual un-met demand exceeds the annual water availability. In these sub-basins, only a part of the un-met demand can be satisfied by additional underground storage. In some other sub-basins, the un-met demand is less than 30% of the SR_{75} of surface runoff. These sub-basins have the potential to meet all the un-met demand with SSS. In the Ramganga sub-basin, the SR_{75} of surface runoff is about 10.1 Bm^3, and approximately 83% of this runoff is occurring during the wet season. To meet the maximum un-met agricultural water demand in the Ramganga sub-basin only requires capturing 33% of the monsoon surface runoff.

Effect of enhanced groundwater recharge on the hydrology

Although surface runoff is available to store in sub-surface as presented in Table 3 and 4, it is pertinent to scrutinize the effect of capturing surface runoff on dry season flows, peak flows in the stream and the downstream water availability. This is demonstrated for the Ramganga sub-basin by simulating hydrological variables for the baseline scenario and two alternative scenarios. The scenarios assume 35% and 65% increase of groundwater recharge compared to the baseline. Increase of groundwater recharge was implemented in the calibrated SWAT model by changing the curve number (CN). Since our goal for running these scenarios is to show the feasibility of storing groundwater for future dry season water demand, we did not considered ground water pumping in the dry season. Volumes of groundwater recharge and the changes of base flow under these scenarios were estimated. Figure 5 shows the mean monthly distribution of base flow and the total stream flow at the main outlet of Ramganga under three scenarios from 1991 to 2010.

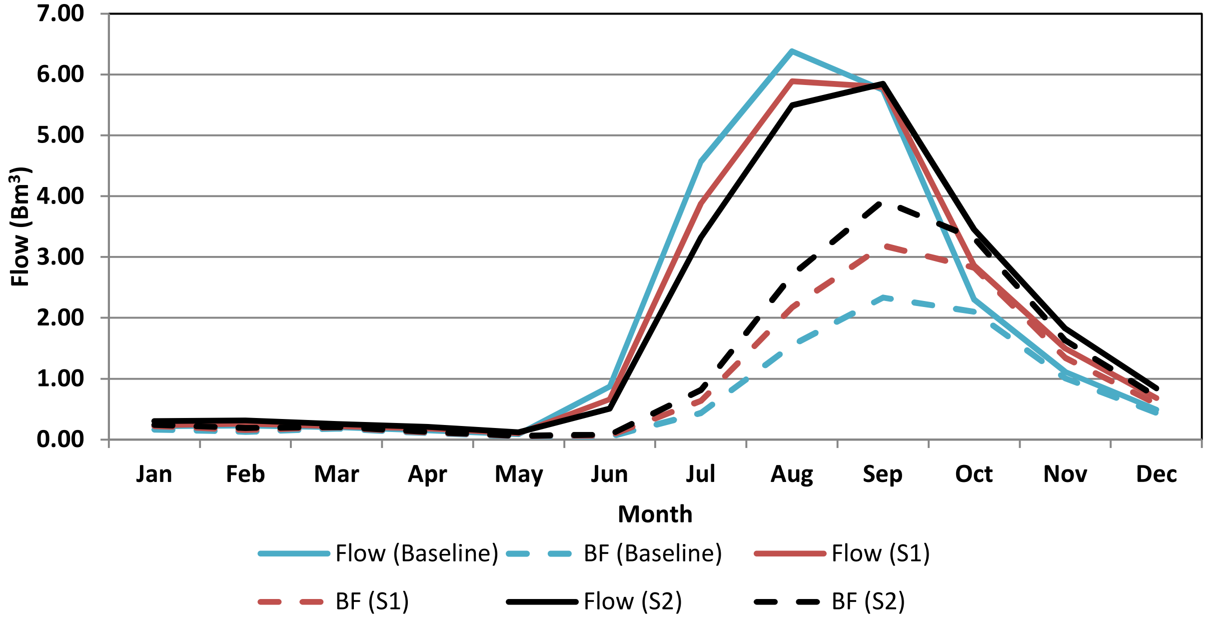

Figure 5: Mean monthly distribution of river flow and base flow in Ramganga sub-basin under different scenarios (BF –Base flow, S1 – Scenario 1, S2 – Scenario 2) (In this simulation groundwater pumping was not considered).

The results reveal that more than 85% of the recharge in Ramganga occurs between July and October and about 80% of the groundwater contribution (base flow) occurs during the period August to November (Figure 5). The analysis shows reduction of river flow during the high flow months of July, August and, September, as compared to the baseline. Under the baseline scenario, the stream flow volume at the sub-basin outlet during this three-month period is 16.7 Bm^3. It reduces to 15.6 Bm^3 and 14.7 Bm^3 respectively when groundwater recharge increased by 35% and 65% compared to the baseline scenario. The overall reduction of high flows under the two scenarios is 6.8% and 12.2% respectively.

As presented in Figure 5, the high base flow occurs during the four-month period from August to November. The baseline scenario indicates about 7.1 Bm^3 of base flow during these four months and it increases to 9.5 Bm^3 and 11.6 Bm^3 when groundwater recharge is increased by 35% and 65% respectively. Further analysis reveals that the annual recharged groundwater left in the aquifer (excluding base flow) increases by 1.25 Bm^3 (35% scenario) and 1.44 Bm^3 (65% scenario), which is about 14% and 16% increase respectively, as compared to the baseline.

This shows that increasing groundwater recharge by 35% would help to increase SSS, which is sufficient to meet 50% and 33% of the unmet agricultural water demand under the two scenarios respectively (Table 4). Further, it shows that the overall increase of base flow during the dry months from January to May is about 24% compared to the baseline scenario. From September to December, the river flow receives substantial portion of water from the groundwater discharge due to the increase of recharge during the high flow months. Therefore as presented in Figure 5, river flow after the rainy season increases. For instance, increase of flow compared to the baseline is 28% and 53% respectively and the increase of base flow is 36% and 65%. Further, during dry months from January to May, the increase of base (without considering groundwater pumping) flow in two scenarios is 18% and 30%.

Effect on floods

The relationship between the simulated maximum monthly river flow and the maximum flood inundated areas in Ramganga is shown in Figure 6. Horizontal axis represents simulated maximum monthly river flow during each year from 2003 to 2010 at the Ramganga outlet. Vertical axis shows the maximum flood inundation areas estimated based on the satellite images in the corresponding year (Amarnath et al., 2012).

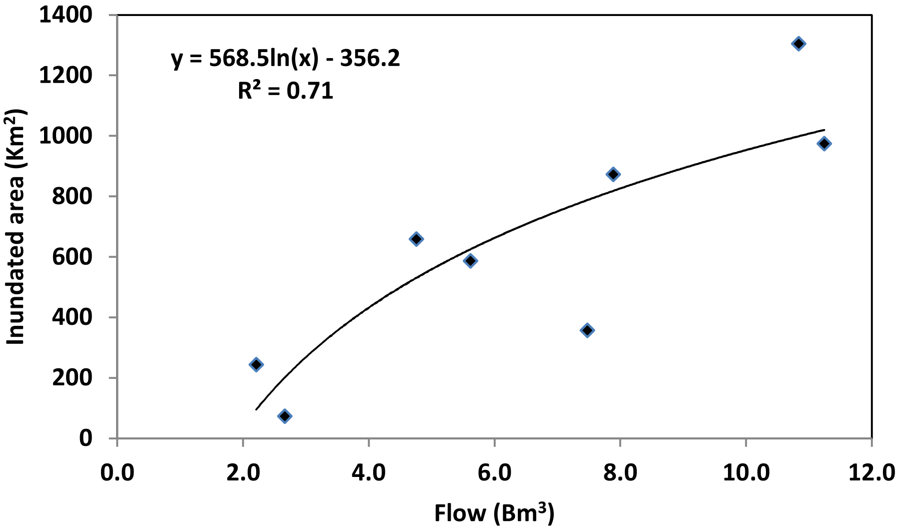

Figure 6: Relationship between annual maximum floods inundated area and the maximum monthly river flow in Ramganga.

The coefficient of determinant (R^2) indicates a strong correlation between area under floods and the annual runoff and this implies that the maximum monthly runoff explain more than 70% of the variation in maximum flood inundated area. The mathematical relationship between maximum flood inundated area and the surface runoff is given in Equation 2:

$$\text{Maximum Flood Inundated area} = 568.7\times \mathrm{Ln}(\text{Flow}) - 356.2 \qquad (2)$$

The maximum monthly flow in Ramganga of about 6.4 Bm^3 in August (Figure 5) has a corresponding flood inundated area of about 700 km^2. Reduction of peak flow to 5.9 Bm^3 (35% groundwater recharge scenario) would reduce the flood-inundated area by about 6.6%. Similarly, the reduction of flood-inundated area compared to the baseline scenario is about 8.0% for 65% groundwater recharge scenario. For this scenario, the reduced outflow from the basin is about 10%. This analysis show the potential impacts of enhanced sub-surface storage on the flooding in the Ramganga sub-basin located in the upstream. The volume of inflow in the Ramganga is negligible compared to the inflow received by the areas such as Bihar in the downstream. Therefore, to understand the potential impacts of SSS on flooding in the GRB, further research is required to investigate the effect of SSS on control of floods in the downstream areas.

Discussion

Water availability and demand analysis conducted in the Ganges River Basin show that there is a substantial mismatch between water demand and supply. For instance, estimated unmet annual water demand for agriculture in the GRB (based on the two scenarios discussed above) ranges from 55.03 Bm^3 to 108.4 Bm^3 while annual total runoff generated in the basin is about 298±99 Bm^3, of which 80% occurs during the monsoon months. In this situation, strategies must be formulated to manage available water in the GRB in more productive manner. One management option discussed in this paper is using SSS…. Augmenting SSS is important in securing downstream water availability for ecosystems and other uses such as agriculture, domestic and industrial.

A thorough analysis of water resource management options requires knowledge of spatial and temporal distribution of water availability and substantial amount of hydrological data. In most cases, such data is not publicly accessible. Thus remote sensing and models are helpful in filling in gaps where data is not available. Models are also helpful in analyzing impact of SSS without making large financial investments. As presented in the results section, SWAT model calibration was conducted using only flow data and the model performance indicates acceptable results. However, the model calibrated for multiple water balance components would have provided more trustworthy simulations. Other observed data such as actual evapotranspiration, soil moisture etc. could have made the model more robust but such data does not exist (although satellite products are there).

Results of the SWAT model demonstrate its capability of estimating the spatial and temporal water availability in the sub-basins of GRB. The outcomes of the model shows its capability of assessing the effect of augmenting SSS on the hydrology of the basin. Flood inundated areas based on satellite remote sensing data (provided by another study) allowed us to investigate impact of SSS on downstream floods. However, the relationship established between floods inundated area and the river flow was only for Ramganga and further investigations are required to understand how SSS will impact on large floods in the downstream part of the basin.

This study focused on spatio-temporal water availability and the impacts of SSS on the hydrology in GRB. Due to limitations of the model, it didn't address the effect of pumping. However, the comparison of the recharge volumes and the base flow presented in the results section indicates the volume of water available in the aquifer for pumping. Detailed modelling exercise that couples both surface and ground water models can be one of the future research direction.

Conclusions

Creating additional SSS beyond the current levels in the Ganges River Basin can simultaneously enhance water supply and control downstream floods. The sub-basin-wise mean annual surface runoff ranges from 2.24 Bm^3 to 35.56 Bm^3, and the contribution of runoff from Nepal is about 63 Bm^3. Several sub-basins in the Ganges River Basin produce sufficiently high dependable annual surface runoff that can be stored underground and used during the dry season. For instance, annual surface runoff in each of the five sub-basins in the upstream of Ganges River Basin is more than 10 Bm^3, which is about 30% of total surface runoff generated in the GRB. Comparison of sub-basin-wise surface runoff with the estimated un-met water demand indicateds that capturing only a portion of the wet-season runoff would be sufficient to provide water to irrigate all the irrigable land in the dry months. Sub-basin-wise river flow analysis in the GRB shows that approximately 30% of the upstream flow to Bihar comes through the Ghaghara and Yamuna Lower sub-basins. This runoff contributes to the recurrent floods in Bihar.

Case study based on Ramganga indicates that increasing 35% and 65% groundwater recharge compared to the baseline scenario may reduce the peak monthly flow by about 6.8% and 12% respectively. Further the net groundwater recharge increases by 14% and 16% respectively. Further, the results indicate that the dry season flow can increase by 18% and 30% in these two scenarios before meeting unmet demand by pumping. Abstracting more water than the net recharge volumes can harm the current water balance and the downstream flows and would need more analysis.

More than 70% of the variations of flood-inundated areas in the Ramganga sub-basin can be explained by the maximum monthly river flow values. By increasing groundwater recharge by 35% and 65% during the peak flow month's flood-inundated area can be reduced by about 6.6% and 8% respectively.

This study only discusses the surface water availability for SSS, and further analysis is needed to ascertain the storage capacity of the aquifer and how much additional storage capacity may be created by pumping groundwater during the dry months. Further, a detailed analysis of the soil, topographic and geological characteristics is required to determine the suitable areas for groundwater recharge.

Finally, to understand the detailed interactions between groundwater and surface water in the sub-basin a coupled groundwater-surface water model is required to run scenarios to investigate the effect of pumping and recharging of groundwater on the hydrology of the basin.

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