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Reviving the Ganges Water Machine: why?

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Abstract

The Ganges River Basin may have a major pending water crisis. Although the basin has abundant surface water and groundwater resources, the seasonal monsoon causes a mismatch between supply and demand as well as flooding. Water availability and flood potential is high during the 3–4 months of the monsoon season. Yet, the highest demands occur during the 8–9 months of the non-monsoon period. Addressing this mismatch requires substantial additional storage for both flood reduction and improvements in water supply. Due to hydrogeological, environmental, and social constraints, expansion of surface storage in the Ganges River Basin is problematic. A range of interventions that focus more on the use of subsurface storage (SSS), and on the acceleration of surface–subsurface water exchange, have long been known as the "Ganges Water Machine". One approach for providing such SSS is through additional pumping prior to the onset of the monsoon season. An important necessary condition for creating such SSS is the degree of unmet water demand. This paper highlights that an unmet water demand ranging from 59 to 119 Bm^3 exists under two different irrigation water use scenarios: (i) to increase *Rabi* and hot weather season irrigation to the entire irrigable area, and (ii) to provide *Rabi* and hot weather season irrigation to the entire cropped area. This paper shows that SSS can enhance water supply, and provide benefits for irrigation and other water use sectors. In addition, it can buffer the inherent variability in water supply and mitigate extreme flooding, especially in the downstream parts of the basin. It can also increase river flow during low-flow months via baseflow or enable the re-allocation of irrigation canal water. Importantly, SSS can mitigate the negative effects of both flooding and water scarcity in the same year, which often affects the most vulnerable segments of society – women and children, the poor and other disadvantaged social groups.

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1 Introduction

The "Ganges Water Machine" (GWM) may be the most opportune solution to the pending water crisis in the Ganges River Basin. Revelle and Lakshminarayana (1975) proposed GWM as an elaborate network of pumping and recharge wells in the rivers and tributaries to irrigate about 38 million hectares (Mha) of potential cropland, and to also capture about 115 billion cubic meters (Bm^3) of monsoon runoff for subsurface storage (SSS). Over the last 40 years, their estimate of gross irrigated area has already been realized, but without the elaborate "water machine" capturing the monsoon runoff. As a result, some areas are experiencing falling groundwater tables. Recurrent floods and droughts batter the basin with increasing frequency. This paper examines the conditions under which the original GWM should be revived as a potential solution to the emerging water woes in the Ganges River Basin.

Millions of people depend upon the river Ganga daily. The basin, with a land area of more than 1 Mha, cuts across four south Asian countries: India, Nepal, Bangladesh and China. The Gangothri Glacier, at an altitude of over 7000 m, is the origin of the river, which traverses through steep slopes and enters the plains at an altitude of 100 m in Haridwar (GoI, 2014). In the plains, it traverses about 2000 km before its confluence with the Brahmaputra and Meghna rivers in Bangladesh.

Benefits of water permeate the landscape of the Ganges. In its meandering course over 2500 km from the Gangothri Glacier to the Bay of Bengal, fertile land and abundant water resources support both livelihoods and food security of more than 600 million people, of whom the majority lives in rural areas (Sharma et al., 2010). River water is an important source for fisheries and other riverine habitats (Payne and Temple, 1996). Navigation extending a stretch of 1500 km and hydropower generation with an installed capacity over 2000 megawatt (MW) is other major financial benefits of the river (GoI, 2014). The river Ganga is also considered sacred and its water is used for many religious and cultural activities, with more than 290 sites set up for tourists to access water along the major rivers and tributaries. Many ecologically sensitive sites,

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including lakes and wetlands, provide numerous other ecosystem services (ESS) (GoI, 2014).

Yet, the intense rainfall during the monsoon season and associated floods, combined with extremely low rainfall during the non-monsoon season and associated droughts, cause severe impacts to the large riparian population. Recurrent floods and droughts affect those vulnerable (the poor, and the women and children) the most. Floods affect millions of people, and damage is caused to hundreds of millions of dollars' worth of property and production, annually (e.g., over 7.5 million people were affected and USD 300 million of damage was caused in 2011 alone, CWC, 2013). Water scarcity in the non-monsoon period barely allows cropping to only about 1.3 times the net sown area (GoI, 2014). Climate change may exacerbate the extreme variability of rainfall and associated streamflow (Hosterman et al., 2012; Gosain et al., 2006; Immerzeel et al., 2010), with associated damage to the rapidly expanding population in the basin.

Building surface storage has been the primary response to buffer the variability of streamflow. The reservoirs in the Indian sub-basin have the capacity to store about 48.7 Bm^3. Further surface storage of 7.6 Bm^3 is planned or under construction (CWC, 2013). When these initiatives are completed, potential surface storage capacity in the Indian sub-basin will be nearly fully developed. Nepal has large surface storage potential that can generate hydropower and augment stream flows during low-flow periods. Yet, less than 1 % of that potential capacity has been developed. The hydro-economic analysis of surface storage in the Ganges River by Jeuland et al. (2013) highlighted that, even if much of the storage potential of Nepal is harnessed, there is still only a limited ability to control the peak flows and floods downstream. What will benefit the Ganges River Basin is an integrated water resources development plan with an improved groundwater management component, which could change the despair to joy for many millions of inhabitants (Sadoff et al., 2013).

This paper proposes the use of SSS as a potential solution to the present-day water storage dilemma, where the flat topography in much of the area, coupled with financial, environmental, social and international constraints, limits large surface storages in the

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basin. SSS is increasingly important now more than ever before for providing sustainable ESS and outcomes. It provides a buffer for rainfall variability, and also provides water that may be used to sustainably intensify and improve agricultural productivity, and for use in the domestic and industrial sectors. SSS also eliminates numerous social and environmental costs associated with the development of large surface storage structures. In addition, the regulation of flow through SSS can help alleviate the social impacts of floods and droughts, especially for women and children who are the hardest hit by such water extremes.

Creation of SSS entails additional pumping of groundwater – out of the aquifers – before the monsoon; this "preparatory" pumping can provide additional water for irrigation and for use in other sectors to enhance the benefits during the non-monsoon months. Provided that subsequent recharge through monsoon rainfall and runoff will replenish the aquifers, the cycle of "pump-deplete-recharge-pump" (PDRP) can ensure sustainability of the enhanced benefits.

The GWM concept is similar to PDRP (Revelle and Lakshminarayana, 1975). The proposal of Chaturvedi and Srivastava (1979) to increase pumping along the perennial and non-perennial tributaries of the Ganges River, and in irrigation canals prior to the onset of the monsoon, resembles the earlier proposed GWM. However, over the past few decades, population expansion and economic growth has led to tremendous changes in the patterns of land and water use as well as water depletion. Moreover, the basin has several mega urban agglomerates (New Delhi, Dhaka, Kolkata and Kathmandu), each having large populations of several million people, and 18 cities having over one million people, and hundreds of cities with over 100 000 people. They all have the potential to accelerate economic growth. Thus, there is an urgent need to determine where, and to what extent, additional SSS can alleviate some of these issues.

The following four conditions are necessary for guaranteeing the success of a PDRP scheme in a given location:

- There must be unmet water demand, which can be used as a reason for depleting a large volume of groundwater resources via pumping.

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- There must be adequate groundwater resources to be pumped before the monsoon.
- There should be adequate monsoon rainfall and runoff to recharge SSS.
- It must be possible to recharge the emptied aquifer using natural surface and subsurface interaction or by artificial methods.

Given the hydrological, socioeconomic and environmental changes that have occurred in the basin over the last 40 years, and with increasing climate change impacts, the above four conditions are vital for reviving the GWM now.

The major objective of this paper is to assess the first condition for ensuring the success of PDRP, i.e., to assess the potential unmet water demand in the basin. Subsequent studies with detailed surface water and groundwater modelling will be performed to assess the remaining three conditions. Many studies show that a significant unmet water demand already exists within the basin or will emerge in the future. Sapkota et al. (2013) showed that considering environmental flows (EFs) in water management will increase the already unmet demand from other sectors in the Upper Ganga River Basin. A substantial yield gap also exists in the major cropping system of rice and wheat in the basin (Aggarwal, 2000). According to several projections, the irrigated area of the basin will have to be increased by another 10–15 Mha from the present level to meet food and livelihood security in the future (GoI, 1999; Rosegrant et al., 2002; Molden, 2007). These studies make it very clear that there is substantial unmet demand for consumptive water use (CWU). The exact locations and quantities of unmet demand throughout the basin, however, have not been defined and are the subject of this study.

2 Water resources of the Ganges River Basin

The four riparian countries: Nepal, India, Bangladesh and China, cover 79, 14, 4 and 3 %, respectively, of the basin area (Fig. 1). While Nepal lies completely inside the

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basin, India and Bangladesh have 26 and 31 % of their land area in the Ganges; and only 0.3 % of the area of China lies within the Ganges.

Table 1 summarizes the overall water resources associated with the four riparian countries. The total renewable water resources (TRWR) of Nepal are estimated as 210 Bm^3, which includes 198 Bm^3 of internal renewable water resources (IRWR)-surface water and 12 Bm^3 inflow from China. All TRWR of Nepal are inflows to India. This inflow and IRWR-surface water and groundwater of 315 Bm^3 make up the India portion of the Ganges TRWR (525 Bm^3), which includes 172 Bm^3 of groundwater from natural recharge.

IRWR from surface water and groundwater resources of the Bangladesh part of the Ganges is estimated as 22 and 5 Bm^3. Thus, TRWR from surface water and groundwater of the Ganges, from the four riparian countries, is estimated as 552 Bm^3.

3 Methodology and data

Our overall goal is to determine the unmet demand for water in the Ganges River Basin (Fig. 1). We begin with an assessment of the recent water use accounts of the Ganges Basin over the period 1998–2011. This analysis follows the water accounting (WA) framework of Molden (1997). The paper then estimates potential unmet irrigation demand of the sub-basins, by considering the irrigated area and water depletion between 2008 and 2011.

Availability of data permits us to conduct the WA analysis only for the Indian portion of the Ganges, which contain 95 % of TRWR and almost all surface storage capacity. Hydrologically, the India portion of the Ganges Basin has 21 major sub-basins, which are those considered by the Central Water Commission (CWC) of India, the main government agency responsible for water resources development and management in the Ganges River Basin. The Yamuna and Son are major rivers draining water to the Ganga from the southern part of the basin. The Ramganga, Ghaghara, Gomti, Gandak and Kosi are major rivers draining water from the northern regions of the basin.

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WA has three main components:

- *Depletion*: part of the inflow depleted through various processes. Depletion includes the following:
  - Process beneficial depletion (evapotranspiration (ET) from the diversions for the intended purposes of producing goods and services).
  - Non-process beneficial ET (ET by the processes where diversions are not intended, such as from homesteads, etc.).
  - Non-process non-beneficial evaporation (evaporation from water bodies and bare soil surfaces).
  - Flows to a sink (a part of the diversions where water quality is deteriorated beyond the use for any productive purposes or cannot be captured for further use).
- *Committed outflow*: part of the water resources intended to meet environmental water needs and inter-basin diversions.
- *Uncommitted outflow*: part of the inflow that is neither committed nor depleted. It is available for further use.

The largest component of depletion, in general, is the process of ET from irrigation, which is the CWU of crops from irrigation. We estimate the monthly CWU from irrigation (IRCWU) of 31 different crops or crop groups across districts in the river basins over the period from 1998 to 2011. The total CWU (TCWU) of different crops can be obtained from Eq. (1) below using the method discussed in Allen et al. (1998).

TCWU of a crop in the jth month is:

$$\mathrm{TCWU}_j = \sum_{k=1}^{4} C_k \cdot \mathrm{ETP}_j \cdot d_{jk} \tag{1}$$

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Where C_k is the crop coefficient of the kth growing period, ETP_j is the potential evapotranspiration of the jth month, and d_{jk} is the number of days of the kth growing period in the ith month.

The CWU from rainfall (RFCWU), which is essentially the effective rainfall, is estimated using the United States Department of Agriculture (USDA) Soil Conservation Service method given in Smith (1992). The RFCWU of the jth month is given in Eq. (2):

$$\text{RFCWU}_j = \begin{cases} (125 - 0.2 \cdot \text{RF}_j) \cdot 125 & \text{if } \text{RF}_j \leq 250\,\text{mm} \\ 125 + 0.1 \cdot \text{RF}_j & \text{if } \text{RF}_j > 250\,\text{mm} \end{cases} \quad (2)$$

RF_j is the rainfall of the jth month, and IRCWU in the jth month is given in Eq. (3), which is the difference between TCWU and RFCWU of different crops.

$$\text{IRCWU}_j = \sum_{i \in \text{all crops}} \max(\text{TCWU}_{ij} - \text{RFCWU}_{ij}, 0) \quad (3)$$

Crops and crop groups considered in the analysis include cereals (rice, wheat, jowar, bajra, maize, ragi, barley and small millets); pulses (gram, arhar/tur and other pulses); oilseeds (groundnut, sesame seed, rapeseed/mustard, linseeds, soybeans, sunflower and other oil crops); potatoes, onions, bananas, and other fruits and vegetables; sugarcane; chili and other spices; cotton; tobacco; fodder; and all other food and non-food crops.

Rice takes up a major part of the cropped and irrigated areas in the *Kharif* season (June–October) (Table 2). Wheat, which is predominantly irrigated, takes up a large part of the cropped area in the *Rabi* season (November–March). A small area of rice is irrigated in the summer (hot weather) season from March to May. Therefore, rice and wheat dominate the cropping patterns of the basin.

Committed streamflow consists of the EFs and inter-basin water transfers. We use the recommendations of Smakhtin and Anputhas (2006) to assess the annual requirement for EFs. Estimates of EFs correspond to managing the river under six different environmental management classes (EMC). EMC A to F varies from natural (pristine) condition to slightly, moderately, largely, seriously and critically modified river conditions. E and F classes are normally considered unacceptable. Although EFs do not influence water management decisions now, we expect them to be under close scrutiny with increasing water abstraction in the basin. Maintaining EFs will be even more prominent in the future, with deteriorating water quality and increasing calls associated with the campaign for a “cleaner Ganga” initiated by the present government (NMCG, 2014).

4 Results

4.1 Snapshot of water use accounts: 2010–2011

In India, TRWR is 525 Bm^3 (Table 1). Of that amount, the potentially utilizable water resources (PUWR) from surface water and groundwater is estimated to be 74 % (or about 388 Bm^3) (Fig. 2, first bar). PUWR includes 250 Bm^3 of surface water and 138 Bm^3 of groundwater (80 % of the natural recharge) (GoI, 1999).

In Fig. 2, the second and third bars summarize the types and sources of depletion associated with CWU. The following is clear from the figure:

- Only 37 % (or about 144 Bm^3) of PUWR was depleted in 2010/11.
- Process CWU accounts for 72 % of the overall depletion, while non-process ET accounts for 22 % and flows to sinks account for 6 % (Fig. 2, second bar).
- Of the process CWU, 77 and 23 % are from groundwater and surface water, respectively (Fig. 2, second bar).
- Irrigation accounts for 93 %, and the domestic and industrial sectors account for 3 and 4 %, respectively, of the process CWU (Fig. 2, third bar).

4.2 Potential for increased water-use efficiency and groundwater development

Figure 2 illustrates that, compared to TRWR, only a small fraction (26 %) is now lost as process and non-process CWU. Moreover, the process CWU from surface water is only 45 % of the surface storage capacity of the basin, indicating that there is enormous potential for increasing water-use efficiency. In addition, only 58 % of the utilizable groundwater resources is currently depleted, indicating substantial potential for increased groundwater development.

It is also possible that some of the water with degraded quality (included in flows to sinks) from one location can become a supply source for downstream locations after mixing with freshwater. Thus, a large portion of TRWR, after accounting for process and non-process CWU, is still available for meeting other uses. This is especially important for many stretches of the river in India and downstream of the Farakka Barrage in Bangladesh. These river reaches have low quality or inadequate flows or both during low-flow months for meeting the ESS and socioeconomic activities (Mirza, 1998; MoEF, 2009; Vass et al., 2010).

Subsurface storage can play a major role in meeting EFs in the low-flow months. Two important elements are missing in the previous annual water accounting procedure. First, annual WA has not considered either the inter-annual and/or intra-annual variability of the supply sources, which are recurrent features in the basin. Second, WA has not considered the minimum requirement for EFs. Ignoring these factors could have major future implications with population expansion, economic growth, and change in lifestyles (Amarasinghe et al., 2007). In addition, all of these factors will be further exacerbated with climate change (Hosterman et al., 2012). The two factors that need to be considered in WA are discussed in brief in the next section.

4.3 Trends of water supply and use

The Ganges River Basin has a sizable quantity of available runoff after meeting all the demand for CWU (Fig. 3a). This is evidenced by the fact that the average flow at

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the Harding Bridge in Bangladesh (just below the Indian border) was 347 Bm^3 during 1973–2009, which is two-thirds of the TRWR of the Indian portion of the basin. From Fig. 3a, we observe the range of dependable streamflows as given below:

- One can expect a discharge of at least 304 Bm^3 75 % of the time, or in at least three of 4 years.
- In an extreme flood year with an average recurrence interval of 10 years, the flow is 436 Bm^3.
- In an extreme drought with an average return period of 10 years, the flow is 271 Bm^3.

Figure 3a illustrates that a sizable quantity of water flows to the sea, even in an extreme drought year. However, annual aggregate flows illustrated in Fig. 3a hide the extremely low flows in the non-monsoon months. The total flow between January and May is only approximately 27 Bm^3 or 4 % of the average annual runoff (Fig. 3). Groundwater as baseflow contributes to much of the low flows, which will not be adequate for meeting the increasing CWU demand of all the sectors, while maintaining adequate flows for the environment.

In an average rainfall year, the three major sectors (agriculture, domestic and industry) deplete close to 150 Bm^3 (Fig. 4). Groundwater contributes to a major portion of the process CWU. The dependence on groundwater, which has increased by 27 % over the last decade, is most prominent in water-stressed years.

The future demand for water in the basin will rapidly increase in the coming decades. Amarasinghe et al. (2007) showed that, under the business-as-usual scenario, CWU demand from surface water will more than double by 2025, while groundwater demands will increase by 60 %. Given the variability of the flow, and the increasing attention for EFs meeting even a fraction of the additional CWU demand, will be a serious challenge in the future.

Aggregate annual figures also hide large intra-annual variation of irrigation CWU (Fig. 5). The process CWU is highest in the *Kharif* season (wet season), but rainfall

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meets a major portion of that demand. Irrigation, which is a critical need for the rest of the year, accounts for 75 % of total process CWU between November and May; this is about 76 Bm^3 of CWU (49 and 27 Bm^3 from groundwater and surface water, respectively), compared to an average flow of 44 Bm^3 in the river during this period.

January to May is the most critical period for meeting any additional water demand in the basin. During this period, the flow of the river is only about 27 Bm^3. However, the additional demand projected in the future could be much higher. For example, according to the projection of Amarasinghe et al. (2007), another 75 Bm^3 will be needed by 2050 for meeting the irrigation CWU alone. If past water-use patterns are an indicator of future use, much of this additional demand will occur in the non-monsoon period.

The projections made by Amarasinghe et al. (2007) are conservative, at best. The projection of gross irrigated area by GoI, a commonly used estimate for policy planning, is set to more than double by 2050 (GoI, 1999), which is another 50 % more than that projected by Amarasinghe et al. (2007). If this is going to be a reality, there could be another 20–30 Bm^3 of additional CWU demand during the non-monsoon months.

4.4 Environmental flows

EFs are an integral portion of the committed flows in water accounts. However, water allocation for EFs has low priority and is not considered in current basin water management plans. The water demand projections of GoI allocated only 20 Bm^3 of the mean annual runoff for EFs in 2050 (GoI, 1999), which is even less than the total flows in the non-monsoon period. However, EF estimates of Smakhtin and Anputhas (2006), based only on the hydrological variability of the basin, is significantly higher than the GOI estimate, and vary from 68 to 12 % of the mean annual runoff. The EMC A (natural [pristine] condition) requires the highest EFs, while EMC F (critically modified condition) required the lowest.

Figure 6 shows the estimates of EFs based on the method by Smakhtin and Anputhas (2006) for managing the river at the level of EMCs A to F. The lowest EF estimate for EMC F, shown by the bottommost blue cross-section (dark blue), is equal to 63 Bm^3. The cumulative totals of the subsequent blue cross-sections show EF estimates for EMCs E to A, i.e., EF estimate for EMC E is 79 (= 63 + 16) Bm^3; EMC D is 105 (= 79 + 26) Bm^3; EMC C is 152 (= 105 + 47) Bm^3; EMC B is 231 (= 152 + 79) Bm^3; and EMC A is 357 (= 231 + 126) Bm^3.

The two line graphs in Fig. 6 show the sum of CWU and the actual annual river flows (solid line), and the sum of CWU and Q_P75 river flows (dashed line). It shows that the average uncommitted flows of the river, at present, is barely adequate to meet the annual EF requirement of EMC A every one out of 4 years, the river is under extreme pressure to maintain the EFs of EMC B. This situation can only exacerbate in the future with increasing demand and deterioration of water quality. By 2050, total ET (process CWU and non-process ET) is projected to be over 235 Bm^3. In such an eventuality, the river flow will often be less than the EFs for EMC B.

Although this analysis does not show EF requirements during the low-flow period, it is clear that EFs are critical for maintaining the health of the river during such periods. Also, importantly, it is during these periods when present river flows are inadequate to meet this EF demand. Moreover, EMCs E and F are generally unacceptable for managing EFs. Therefore, the monthly flows required under EMCs A to D and the implications of maintaining them in the river are important for water management in the basin.

Regardless of the magnitude of EF estimates and CWU projections, it is clear that irrigation will account for a major part of the additional water depletion in the basin. Furthermore, much of this additional CWU demand will be required during low-flow periods. With the recent attention given to the "cleaner Ganga" campaign, more flows are also required in the river during this period. Thus, additional storage, whether surface or underground, is critical for meeting the future water requirements of the basin. However, due to social and environmental constraints for additional surface storage, the potential solution to augment water supply during the low-flow period is additional SSS.

5 Potential unmet CWU demand of sub-basins

The only feasible strategy for creating additional SSS is via additional pumping and depletion (ET) of groundwater before the monsoon season. According to land- and water-use patterns, there is a potential for preparatory pumping in the in the *Rabi* and summer (hot weather) seasons. This can be illustrated by the irrigated and cropped areas (Fig. 7) and monthly CWU (Fig. 5).

In the *Kharif* season, the irrigated area is low (only 43 % of the cropped area) and irrigation CWU is even lower (only 16 % of the total CWU) due to monsoon rains. In contrast, the irrigated area is 75 % of the total cropped area, and irrigation CWU is 94 % of the total CWU in the *Rabi* season. This shows that the additional irrigated area in the *Rabi* season can result in a proportionally larger irrigation CWU. If groundwater meets this additional irrigation CWU, it can create additional SSS. The months of April and May have relatively higher CWU. Therefore, any additional irrigation during these 2 months requires even higher irrigation CWU, and hence has the potential for creating higher SSS.

We consider two scenarios to assess the potential SSS (Table 3) that can be created with preparatory pumping at the sub-basin level in the Ganges River Basin.

- Scenario 1 assesses the potential for increasing gross irrigated area in the *Rabi* and hot weather seasons. Here, groundwater pumping will be increased only to bridge the gap between actual and net irrigated area.

- Scenario 2 assesses the potential for increasing the gross cropped area in the *Rabi* and hot weather seasons. Here, groundwater pumping will be increased to bridge the gap between actual and net sown area.

The highest potential for SSS exists in the Yamuna Lower, Bhagirathi, Son, Damodar and Kali Sindh sub-basins (Fig. 8). For example, in the Yamuna Lower Sub-basin, the maximum irrigated and cropped areas of 3.64 and 6.19 Mha, respectively, are achieved in the *Rabi* season. Hardly any area is cropped or irrigated in April and May. Therefore, the following is possible in the Yamuna Lower Sub-basin:

- Under scenario 1, it is possible to irrigate another 0.22 Mha in the *Rabi* season and close to 3.82 Mha in the hot weather season. Therefore, the additional irrigable area of 4.04 Mha could account for 7.8 Bm^3 of groundwater irrigation CWU.

- Under scenario 2, it is possible to irrigate another 2.55 Mha in the *Rabi* season, and 6.15 Mha in the hot weather season. This additional area could account for another 18.7 Bm^3 of groundwater.

In the Bhagirathi sub-basin, the maximum cropped and irrigated areas are achieved in the *Kharif* season. The irrigated area in the *Rabi* season is less than one-third of the irrigated area and only 10 % of the cropped area in the *Kharif* season. So, there is potential for increasing irrigation in the *Rabi* season. There is similar potential for such an increase between April and May. This has the potential to deplete 4.6–15.1 Bm^3 of water for irrigation and, in particular, create SSS from groundwater irrigation.

Similarly, the Ramganga sub-basin in the upstream has the potential to create 2.5–3.2 Bm^3 of SSS through additional groundwater irrigation. However, unlike the Yamuna Lower and Bhagirathi sub-basins, much of this potential exists only through irrigation between April and May.

Table 3 shows that all sub-basins in the Ganges River Basin have the potential to deplete between 59 and 119 Bm^3 of groundwater under scenarios and 1 and 2, respectively. This potential groundwater depletion can be further increased, if groundwater can replace a part of current CWU from canal irrigation. The CWU from canal irrigation can be re-allocated to increase river flow during the low-flow period.

Whether such quantities can actually be depleted on an annual basis depends on many other hydrologic factors, which include the following:

- Feasibility and sustainability of additional groundwater pumping without creating environmental disbenefits.

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- Magnitude of the current monsoon runoff in sub-basins, which is available for recharging SSS.

- Ability to recharge SSS through monsoon runoff, using natural or artificial interaction of surface water and groundwater.

Detailed surface water and groundwater modelling studies would be needed to assess these concerns. Other factors that determine the potential benefits of SSS include the following:

- Properties of the soil, and the "crop holidays" (a period of time when the cultivation of a particular crop does not take place) required for the soil in between intensive cropping in the *Rabi* and *Kharif* seasons.

- People's willingness to increase cropping and irrigation intensities to 300 %.

- Access to energy for additional pumping.

- Economic assessment of optimal re-allocation of water under various SSS strategies.

These require agronomic feasibility studies, reduction of the dependency on electricity for pumping, feasibility of using alternative energy sources such as solar, and analysis of the social and economic costs, benefits and trade-offs of various surface and subsurface storage plans.

6 Conclusions

This paper shows that the basin has a highly seasonal hydrology with an enormous intra-annual mismatch between water supply and demand, which is expected to increase due to a variety of socioeconomic factors. While a major portion of the water supply comes from the 3–4 months of the monsoon, a considerable part of the demand occurs during the 8–9 months of the non-monsoon period. Addressing this severe and widening mismatch between supply and demand requires substantial additional storage capacity. Without additional storage, a large part of the basin's riparian population of 600 million people will face severe and continuously escalating water shortages.

Due to hydrogeological, environmental and social limitations, expanding surface storage in the basin is difficult and often infeasible. The potential solution is to revive the GWM, i.e., creating additional SSS. The way to create such storage is through additional pumping of groundwater before the onset of the monsoon season. One of the necessary conditions for creating this SSS is ensuring there is any unmet demand, thus providing an excess water supply for subsurface storage. This analysis finds that between 59 and 119 Bm^3 of unmet demand exists beyond the current water use under two different irrigation water-use scenarios. The first scenario increases the gross irrigated area in the *Rabi* and hot weather seasons. The second scenario increases the gross cropped area in the *Rabi* and hot weather seasons.

Moreover, although critical for the health of the river, water allocation for EFs is not part of the current water management plans of the basin. This practice has to change, as many stretches of the river have an unacceptable level of low flows in the dry season. The annual flows required to manage the river at a desirable level of EMCs range from 357 Bm^3 under natural (pristine) condition to 231, 152 and 105 Bm^3 under slightly, moderately and largely modified conditions, respectively.

Managing the EFs of the river under the slightly modified condition, let alone the pristine condition, will be extremely difficult with the increasing water demand as a result of population and economic growth. The most challenging aspect of EF management even under the moderately modified condition is to maintain the required flows during the low-flow period. This requires substantial changes to water releases from the reservoir and re-allocation of canal irrigation in the dry season, when irrigation demand is the highest. Given the limited potential of surface storage in the basin, augmenting SSS is the best potential option for re-allocating canal water and also for increasing baseflows during the non-monsoon period.

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Whether such a potential of SSS can be created through additional pumping of groundwater and subsequent recharge via monsoon runoff require further hydrogeological and economic analyses. However, the benefits of developing only a small portion of such potential storage can be enormous, because SSS can enhance sustainable water supplies, and provide benefits for irrigation and other water-use sectors. It can buffer rainfall variability and reduce extreme flooding, especially in downstream regions. SSS can increase river flow during the low-flow months either through baseflow or reallocation of canal irrigation. Importantly, it can mitigate the negative effects of floods and water scarcity in the same year, which often affects the most vulnerable people of society – women and children, the poor and other disadvantaged social groups.

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Table 1. Water resources of the riparian countries of the Ganges River.

Countries	IRWR-surface water (Bm^3)	IRWR-groundwater (Bm^3)	Inflow from other countries (Bm^3)	TRWR (Bm^3)	Storage capacity (Bm^3)
China	12	–	–	12	–
Nepal	198	20[a]	12[c]	210	0.09
India	143	172	210[d]	525	53.00
Bangladesh	22	5[b]	525[e]	552	0.02
Ganges	375[f]	177	–	552	53.10

Sources: AQUASTAT database (FAO 2014); GoI (1999)
Notes: [a] all overlap with surface water; [b] no overlap with surface water; [c] inflow from China to Nepal, [d] inflow from Nepal to India, [e] inflow from India to Bangladesh, [f] includes inflow from China.

Table 2. Cropped and irrigated areas of major crops grown in the basin.

Crop	Cropped area (Mha)		Irrigated area (Mha)	
	1998–1999 to 2000–2001	2008–2009 to 2010–2011	1998–1999 to 2000–2001	2008–2009 to 2010–2011
Rice – *Kharif*	14.6	13.8	6.9	7.6
Rice – *Rabi*	0.5	0.3	0.4	0.3
Rice – Summer	1.4	1.3	1.5	1.5
Wheat – *Rabi*	17.2	17.4	14.9	16.0
Maize	2.7	2.5	0.7	0.6
Other cereals – *Kharif*	3.9	3.8	0.2	0.3
Other cereals – *Rabi*	0.6	0.4	0.3	0.3
Pulses	7.5	7.1	1.6	1.8
Oilseeds	7.8	7.3	1.8	2.4
Vegetables/roots	2.1	2.0	1.0	1.2
Fruits	0.6	0.5	0.2	0.2
Sugar	2.2	2.4	1.9	2.1
Cotton	0.1	0.1	0.06	0.05
Others	4.3	7.6	2.1	1.4
Total	65.5	66.5	33.6	35.8

Estimates based on district-wise data from the Directorate of Economics and Statistics, Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India (GoI).

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Table 3. Scenarios of potential increases in groundwater CWU demand.

	Basin	Net irrigated area	Total irrigation CWU	Maximum monthly irrigated area			Maximum monthly cropped area			Potential increase in in irrigated area[2] Scenario 1		Scenario 2		Irrigation CWU		Increases in groundwater CWU[3] Scenario 1		Scenario 2	
				Jun–Oct	Nov–Mar	Apr–May	Jun–Oct	Nov–Mar	Apr–May	Nov–Mar	Apr–May	Nov–Mar	Apr–May	Nov–Mar	Apr–May	Nov–Mar	Apr–May	Nov–Mar	Apr–May
		Mha	Bm^3	Mha	Mha	Mha	Mha	Mha	Mha	Mha	Mha	Mha	Mha	mm	mm	Bm^3	Bm^3	Bm^3	Bm^3
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
1	Above Ramganga confluence	1.35	1.51	0.80	1.35	0.36	1.22	1.51	0.37	0.00	0.99	0.16	1.15	274	173	0.00	1.71	0.45	1.99
2	Banas	0.99	2.64	0.48	0.99	0.00	1.71	1.64	0.01	0.00	0.98	0.72	1.70	276	123	0.00	1.21	1.99	2.10
3	Bhagirathi and others[1]	1.78	4.33	1.70	0.50	0.42	4.75	2.12	0.92	1.27	1.35	4.24	4.32	230	124	2.93	1.67	9.78	5.35
4	Chambal Lower	0.41	0.62	0.22	0.39	0.00	0.40	0.53	0.00	0.02	0.41	0.14	0.53	272	190	0.06	0.77	0.38	1.00
5	Chambal Upper	1.08	2.09	0.50	0.92	0.01	1.57	1.38	0.01	0.16	1.07	0.65	1.57	333	190	0.53	2.04	2.17	2.97
6	Damodar[1]	0.96	2.14	0.96	0.10	0.10	2.89	0.96	0.20	0.86	0.86	2.79	2.79	231	201	1.99	1.74	6.44	5.62
7	Gandak and others	1.55	2.47	1.00	1.18	0.08	1.91	1.63	0.24	0.37	1.47	0.73	1.83	269	284	0.99	4.17	1.97	5.20
8	Ghaghara	3.01	4.03	1.76	2.95	0.49	3.35	3.50	0.68	0.06	2.52	0.55	3.01	288	197	0.16	4.95	1.58	5.91
9	Ghaghara and Gomti confluence	1.39	1.64	1.10	1.10	0.04	1.29	1.28	0.05	0.29	1.35	0.19	1.25	294	186	0.85	2.51	0.56	2.33
10	Gomti	1.48	1.63	1.03	1.36	0.16	1.21	1.52	0.19	0.11	1.32	0.15	1.36	303	173	0.34	2.29	0.47	2.36
11	Kali Sindh	1.96	3.10	1.04	1.50	0.01	2.71	2.21	0.01	0.46	1.95	1.21	2.70	307	127	1.42	2.48	3.71	3.43
12	Kosi	0.70	1.29	0.45	0.65	0.10	1.05	0.87	0.23	0.05	0.60	0.40	0.94	241	150	0.13	0.90	0.97	1.42
13	Ramganga	1.68	1.85	1.36	1.68	0.42	1.60	1.84	0.44	0.00	1.25	0.16	1.42	298	197	0.00	2.46	0.49	2.79
14	Son	0.74	3.24	0.43	0.51	0.02	2.69	1.35	0.07	0.23	0.72	2.19	2.68	314	165	0.73	1.19	6.87	4.41
15	Tons	0.32	0.82	0.14	0.28	0.00	0.59	0.65	0.00	0.03	0.32	0.37	0.65	311	184	0.10	0.58	1.15	1.19
16	Upstream of Gomti	1.95	2.21	1.15	1.95	0.23	1.55	2.17	0.24	0.00	1.72	0.21	1.93	278	171	0.00	2.93	0.60	3.30
17	Yamuna Lower	3.86	7.18	1.71	3.64	0.05	4.53	6.19	0.05	0.22	3.82	2.55	6.15	282	187	0.62	7.13	7.18	11.5
18	Yamuna Middle	2.14	2.47	1.04	2.14	0.06	1.44	2.46	0.06	0.00	2.08	0.32	2.40	249	164	0.00	3.41	0.79	3.93
19	Yamuna Upper	2.76	2.78	1.65	2.76	0.52	2.10	3.23	0.54	0.00	2.24	0.47	2.71	231	166	0.00	3.72	1.08	4.50
20	Ganges–India	30.1	48.1	18.5	25.9	3.1	38.6	37.0	4.34	4.15	27.0	18.1	41.1	274	173	10.9	47.9	48.6	71.3

Source: Authors' estimation.
Notes: [1] Most of the cropping in the *Kharif* season starts in May. Therefore, the three periods are May–September, October–February and March–April.
[2] C9 = C1 – C4; C10 = C1 – C5; C11 = MAX(C6, C7) – C4; C12 = MAX(C6, C7) – C5.
[3] C15 = C9 · C13/100; C16 = C10 · C14/100; C17 = C11 · C13/100; C18 = C12 · C14/100.

Table A1. Acronyms.

CWC	Central Water Commission
CWU	Consumptive water use
EMC	Environmental management class
ESS	Ecosystem services
ET	Evapotranspiration
GoI	Government of India
GWM	Ganges Water Machine
IRCWU	Consumptive water use from irrigation
IRWR	Internal renewable water resources
PUWR	Potentially utilizable water resources
RFCWU	Consumptive water use from rainfall
SSS	Subsurface storage
TCWU	Total consumptive water use
TRWR	Total renewable water resources
WA	Water accounting

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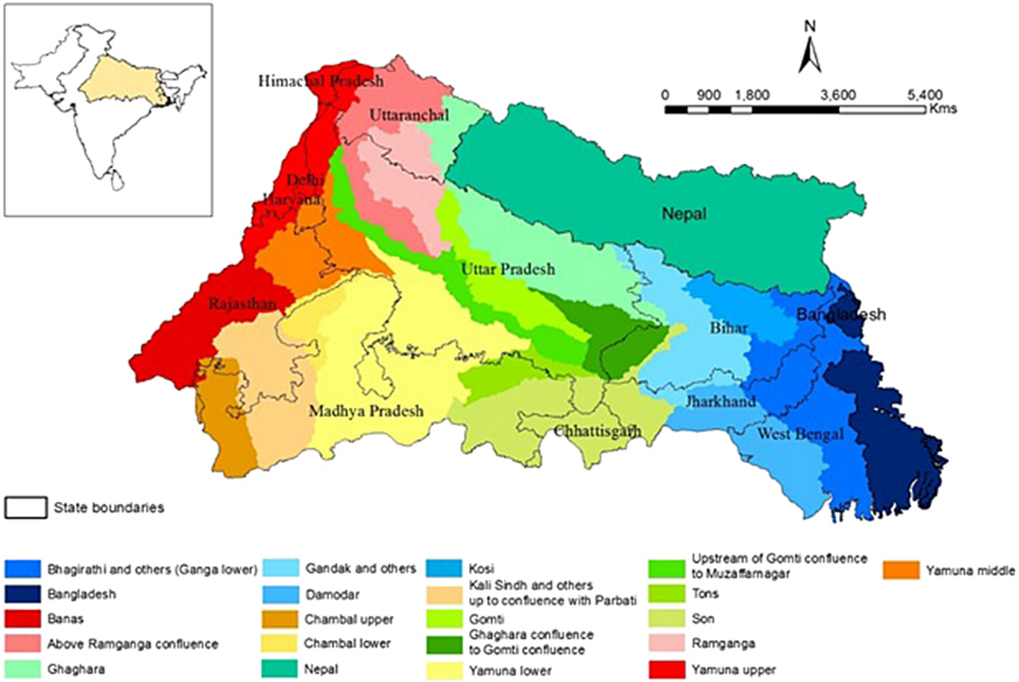

Figure 1. Ganges River Basin and its sub-basins.

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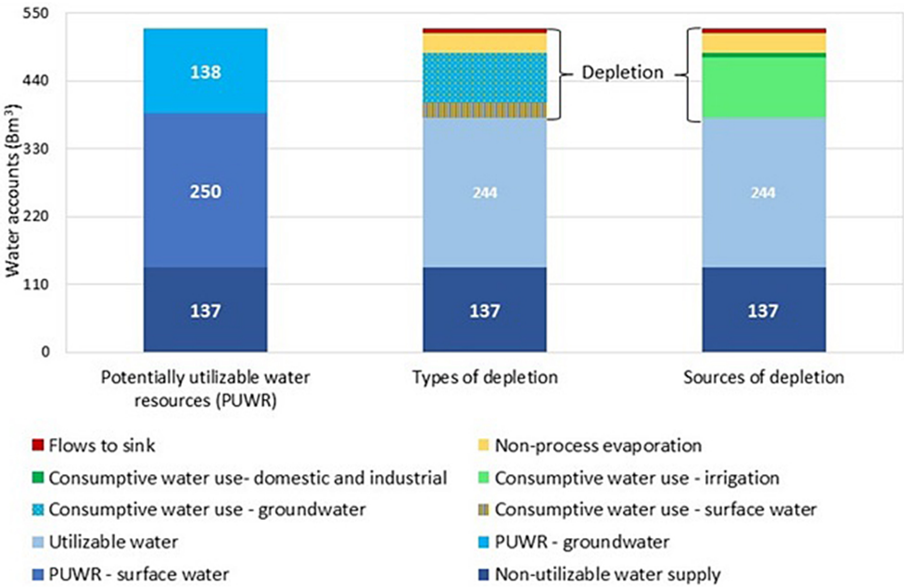

Figure 2. Water use accounts in the Ganges River Basin (2010–2011). Sources: utilizable surface water, groundwater and non-utilizable water figures are from GoI (1999). Other water accounting figures are authors' estimates.

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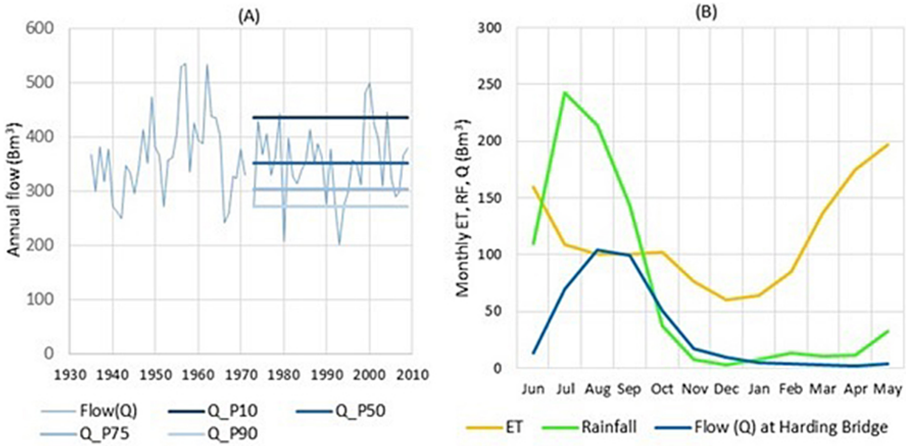

Figure 3. (a) River flow at the Harding Bridge, and **(b)** average monthly ET, rainfall (RF) and river flow at Harding Bridge between 1998 and 2008. Sources: rainfall (Indian Meteorological Department), ET (University of East Anglia, Climatic Research Unit, Norwich, UK, 2014); river flow (Institute of Water Modelling, Dhaka, Bangladesh); and effective rainfall are authors' estimates.

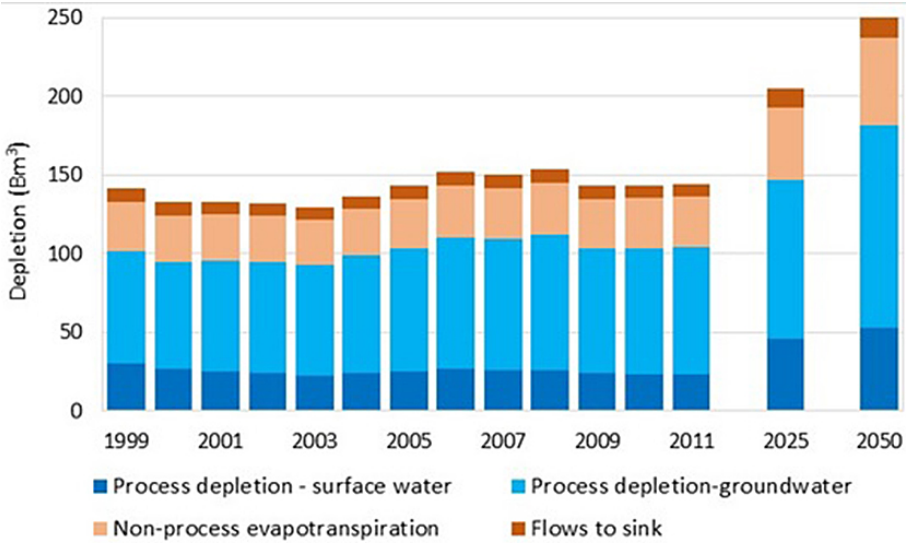

Figure 4. Water use in the Ganges River Basin – past trends and projections. Source: trends (1999–2011) are author's estimates. The projections are from Amarasinghe et al. (2007).

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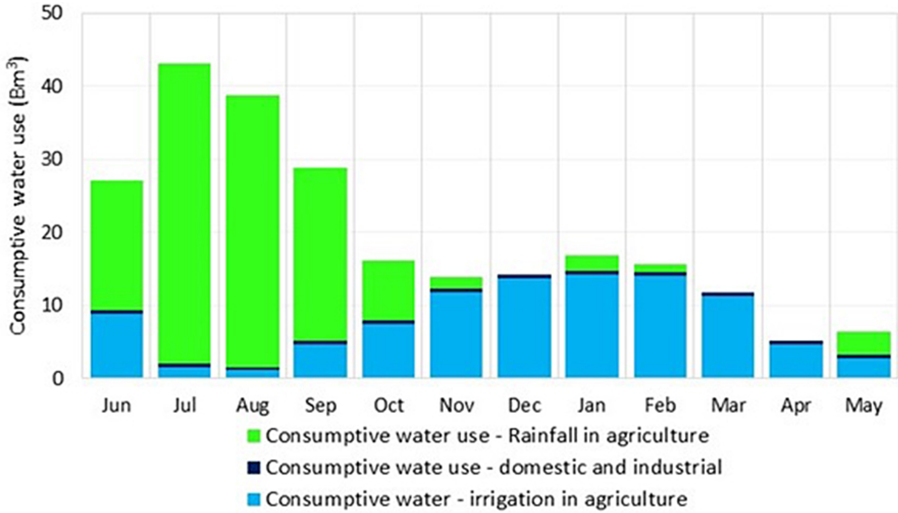

Figure 5. Average monthly CWU between 1999 and 2011.

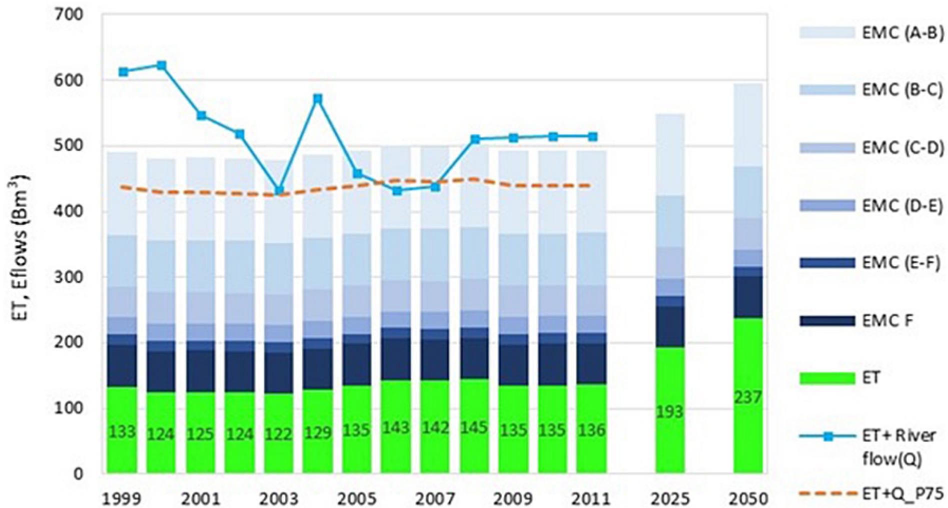

Figure 6. ET and EF estimates for different EMCs.

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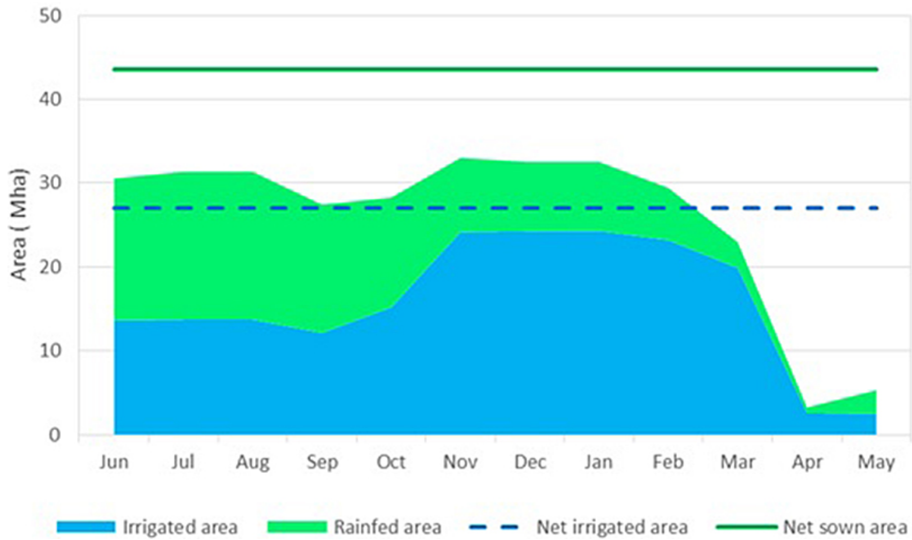

Figure 7. Monthly actual and net irrigated and cropped areas in the Ganges River Basin (2008–2011).

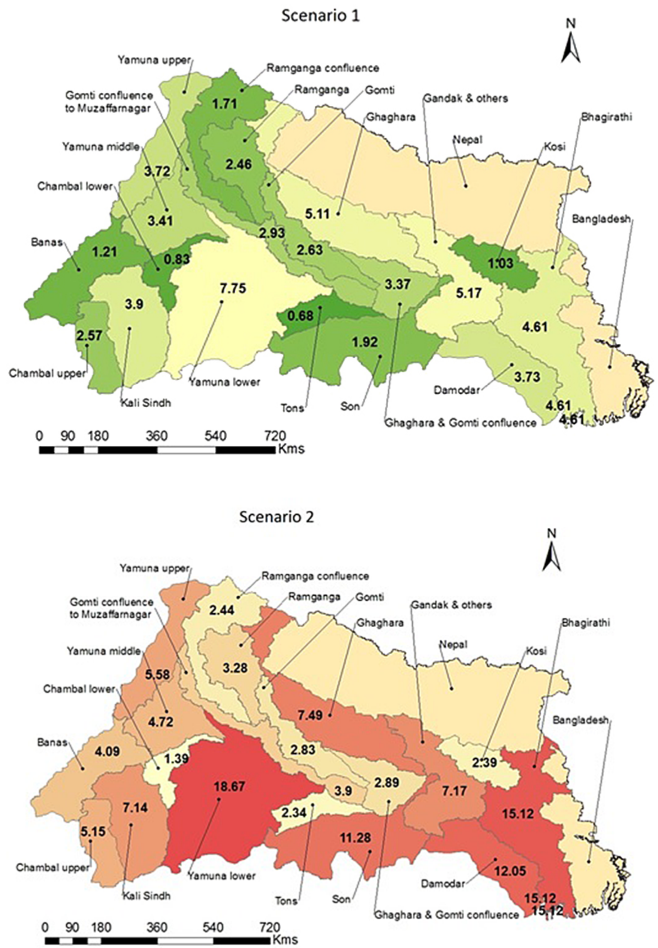

Figure 8. Scenarios of potential unmet water demand of the sub-basins in the Ganges River Basin (Indian part).

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