Reviving the Ganges Water Machine: Potential

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Abstract

The Ganges River Basin faces severe water related challenges related to a mismatch between supply and demand. 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 (June to September) of the monsoon season. Yet, the highest demands occur during the 8-9 months (October to May) of the non-monsoon period. Addressing this mismatch, which is likely to increase with increasing demand, 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, has long been known as the 'Ganges Water Machine'. The approach of GWM for providing such SSS is through additional pumping and depleting the groundwater resources prior to the onset of the monsoon season and recharging the SSS through monsoon surface runoff. An important condition for creating such SSS is the degree of unmet water demand. The paper shows that the potential unmet water demand ranging from 59 to 124 Bm^3/year exists under two different irrigation water use scenarios: (i) to increase irrigation in *Rabi (November to March)* and hot weather (April to May) seasons in India, and Aman (July-November) and Boro (December to May) seasons in Bangladesh to the entire irrigable area, and (ii) to provide irrigation to *Rabi* and hot weather season in India and Aman and Boro seasons in Bangladesh to the entire cropped area. However, the potential for realizing the unmet irrigation demand ~~through SSS~~ is high only in 7 sub-basins in the northern and eastern parts, is moderate to low in 11 sub-basins in the middle, and has little or no potential in 4 sub-basins in the western part of the Ganges Basin. Overall, a revived GWM plan has the potential to meet 45-84 Bm^3/year of unmet water demand.

Key words: Ganges water machine, subsurface storage, runoff, groundwater, irrigation, unmet demand

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

PDRP - Pump-deplete-recharge-pump

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

Reviving the 'Ganges Water Machine': Potential?

1. Introduction

Millions of people depend upon the River Ganga. The Ganges River Basin, with a land area of more than 1 million hectare (Mha), cuts across four south Asian countries, with ~~:~~ India, Nepal, Bangladesh and China taking up ~~.~~79%, 14%, 4% and 3% of the area of the Basin. The Gangothri Glacier, at an altitude of over 4000 to 7,000 m, is the origin of the river, which traverses through steep slopes and enters the plains at an altitude of 300 m in Haridwar (GoI 2014). In the plains, it traverses about 2,000 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 2,500 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), and also for navigation extending a stretch of 1,500 km. Hydropower generation with an installed capacity over 2,000 megawatts ~~(MW)~~ is a major financial benefits of the river (GoI 2014). The River Ganga is also considered sacred and revered by its riparian population, and ~~. Moreover,~~ 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, including lakes and wetlands, provide numerous ecosystem services ~~(ESS)~~, including maintenance of aquatic organisms for food and medicine, and a space for flood control and nutrient recycling, and maintaining water quality.

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 the vulnerable population (the poor, and the women and children) the most (Douglas, 2009). 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, both physical and economic in the non-monsoon period due to inadequate water supply or insufficient development respectively, barely allows cropping to only about 1.3 times the net sown area (GoI 2014).

Climate change may exacerbate the water related issues due to extreme variability of rainfall and associated streamflow, although the projections for the Ganges Basin are widely divergent. Hosterman et al., 2012 and~~;~~ Immerzeel et al., 2010 projected a decrease in annual rainfall, while Sharmila et al., 2015 and Kumar et al., 2011 show an increase in monsoon rainfall and longer monsoon seasons. The latter also projected an increase in dry spells during the monsoon, implying that the intensity of precipitation in the rainfall events will increase. However, according to Lutz et al., ~~(~~2014~~)~~ water availability in the upstream and also in the low flow periods will increase. While any increase in rainfall, especially in the non-monsoon period, is a good opportunity, any increase in variability of rainfall could be a challenge for water management in the Basin. Unless there is adequate storage to buffer the variability, most climate change scenario projections could increase the impacts of floods and droughts substantially on the rapidly expanding population in the Basin.

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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 billion cubic meters (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 (FAO 2014). 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).

The "Ganges Water Machine" (GWM), proposed by Revelle and Lakshminarayana (1975), may be the most opportune solution to the severe water challenges in the Ganges River Basin. The ~~Revelle and Lakshminarayana (1975) proposed~~ GWM entails: A) increasing infiltration by spreading flood water over the land area by constructing bunds, and increasing seepage from irrigation canals by spreading the canal network, and B) pumping and depleting groundwater from the aquifers during the pre-monsoon period to create sufficient sub-surface storage (SSS), and subsequently recharging the SSS by natural or artificial means during the monsoon period. ~~as an elaborate network of pumping and recharge wells in the rivers and tributaries to~~ The GWM envisaged to irrigate about 38 Mha of potential cropland, and to also capture about 115 Bm^3/year ~~-~~of monsoon runoff for subsurface storage (SSS). Over the last 40 years, their estimate of gross irrigated area has already been realized (Amarasinghe et al., 2007).~~, but without the elaborate “water machine” capturing the monsoon runoff.~~ As a result, some areas are experiencing falling groundwater tables (Gleeson et al., 2012), of which at least a part could have been avoided with the GWM. Recurrent floods and droughts batter the basin with increasing frequency. There is already a mismatch between supply demand, and the water challenges are likely to increase with increasing demand. This paper examines the conditions under which the original GWM concept ~~sh~~could be revised ~~ved~~ as a potential solution to the emerging water problems in the Ganges River Basin.

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 basin. SSS is now more important than ever before for providing sustainable eco-systems services ~~ESS~~ for livelihoods and benefits. It provides a buffer for rainfall variability. SSS also provides water for irrigation to increase cropped area, and water 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 to guarantee 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 via pumping.
- There must be an adequate volume of groundwater available for pumping before the monsoon season.
- 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 concept now.

The major objective of this paper is to assess the potential for reviving the GWM in terms current water use, availability and potential unmet demand at sub-basins in the Ganges. Subsequent studies with detailed surface water and groundwater modelling will be conducted to assess the potential locations, quantities and the mode of recharge for increasing the PDRP and a sustainable GWM.

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 for 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 next 2-3 decades (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

Of the ~~The~~ four riparian countries (Figure 1), ~~: Nepal, India, Bangladesh and China, cover 79%, 14%, 4% and 3%, respectively, of the basin area (Figure 1). While~~ Nepal lies completely inside the basin, India and Bangladesh have 26% and 31% of their land area in the Ganges Basin; and only 0.3% of the area of China lies within the Ganges.

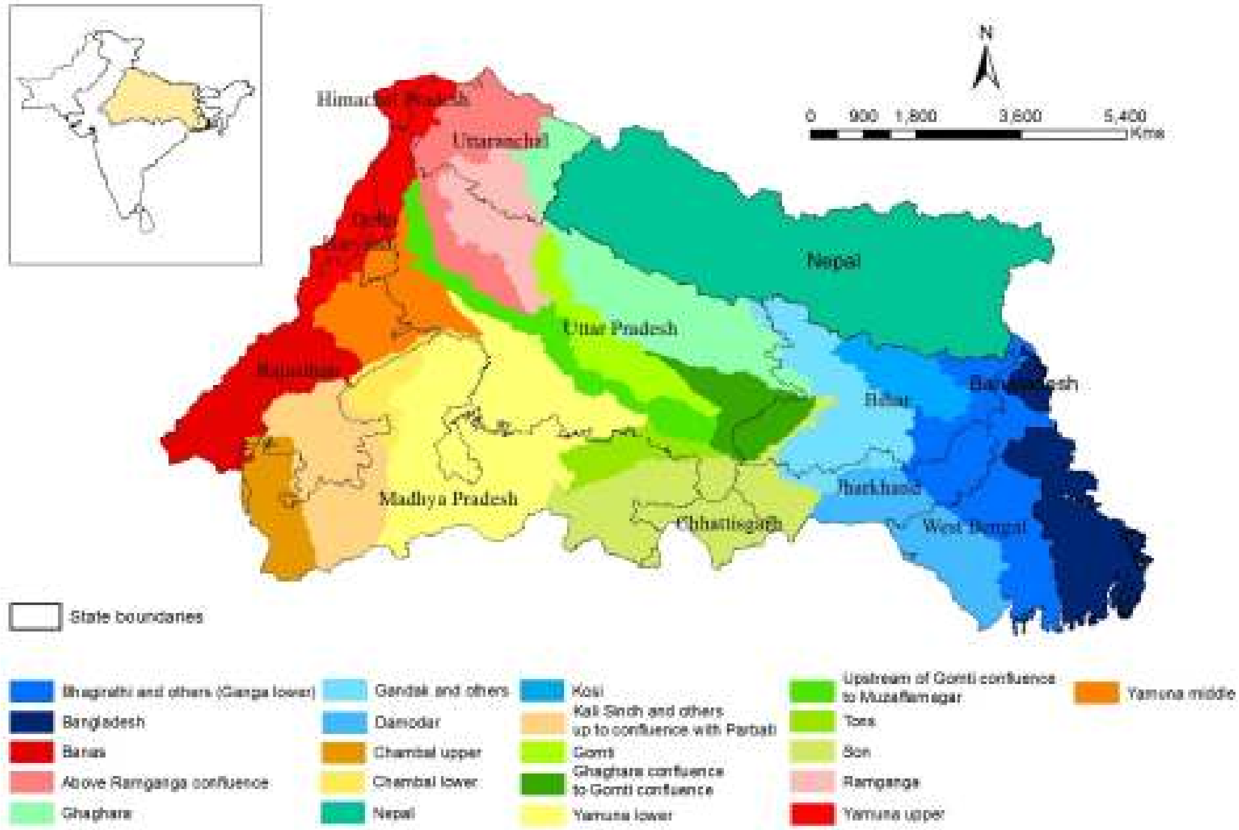

Figure 1. Ganges River Basin and its sub-basins.

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

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

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

Countries	IRWR-surface water (Bm^3/year)	IRWR-Groundwater (Bm^3/year)	Inflow from other countries (Bm^3/year)	TRWR (Bm^3/year)	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.

3. Methodology and Data

Our overall goal is to determine the potential for meeting the unmet water demand through SSS in the Ganges River Basin (Figure 1). We begin with an assessment of the recent water use accounts of the Ganges Basin over the period 1998 to 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. Finally, the unmet demand is compared with the present level of uncommitted surface water and groundwater resources for assessing the potential sub-basins for PDRP to enhance SSS.

This paper conducts the WA analysis only for the Indian and Bangladesh riparian regions, which contain almost all TRWR, surface storage capacity and irrigation in the Ganges Basin. 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. The Bangladesh riparian area includes the Rajshahi, Kulna, Barisal and parts of Dhaka administrative divisions.

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 equation (1) below using the method discussed in Allen et al, (1998).

TCWU of a crop in the jth month is:

$$TCWU_j = \sum_{k=1}^{4} C_k \times ETP_j \times d_{jk} \qquad (1)$$

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 equation (2):

$$RFCWU_j = \begin{cases} \left(125 - 0.2 \times RF_j\right) \times 125 & if\ RF_j \leq 250\ mm/month \\ 125 + 0.1 \times RF_j & if\ RF_j\ > 250\ mm/month \end{cases} \qquad (2)$$

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

$$IRCWU_j = \sum_{i \in all\ crops} \max(TCWU_{ij} - RFCWU_{ij}, 0) \qquad (3)$$

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.

In India, rice takes up a major part of the cropped and irrigated areas in the *Kharif* season (June to October) (Table 2). Wheat, which is predominantly irrigated, takes up a large part of the cropped area in the *Rabi* season (November to March). A small area of rice is irrigated in the summer (hot weather) season from March to May. In Bangladesh, rice is the dominant crop taking up 87% of the gross cropped area in the three seasons of Aus (May to August), Aman (July to November) and Boro (December to April). Therefore, rice and wheat dominate the cropping patterns of the basin.

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

Crop	Cropped area (Mha/year)		Irrigated area (Mha/year)	
	1998-1999 to 2000-2001	2008-2009 to 2010-2011	1998-1999 to 2000-2001	2008-2009 to 2010-2011
Indian riparian region				
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
Bangladesh riparian region				
Rice – Aus	-	0.6	-	0
Rice – Aman	-	3.1	-	0.5
Rice – Boro	-	2.4	-	2.3
Others	-	1.3	-	1.1

Total	65.5	73.9	33.6	39.6

Source: 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), and Bangladesh Bureau of Statistics

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 vary 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).

The average monthly ETP and rainfall (RF) estimates for the districts are obtained from the University of East Anglia, Climatic Research Unit and Indian Meteorological Department respectively. The district level cropped and irrigated areas are collected from the data published at the website of the Directorate of Economic and Statistics website, Department of Agriculture and Corporation, Ministry of Agriculture (http://lus.dacnet.nic.in/). The crop coefficients, crop growth stages, and cropping calendar are obtained from FAO AQUASTAT data base (<http://www.fao.org/nr/water/ aquastat/water_use_agr/Annex1.pdf>), FAO irrigation and Drainage paper 56 (Allen et al., 1998), and from the Agricultural Statistics at a Glance publications by the Directorate of Economic and Statistics, Department of Agriculture India (http://eands.dacnet.nic.in/PDF/Agricultural-Statistics-At-Glance2014.pdf/). The agricultural statistics of Bangladesh districts are collected from various publications of the "Year Book of Agricultural Statistics of Bangladesh", published by the Bangladesh Bureau of Statistics (http://www.bbs.gov.bd/Page WebMenuContent.aspx?MenuKey=234).

The estimates of the total cropped and irrigated area and the CWU of the sub-river basins are the aggregate of the estimates obtained for districts. When a district cuts across more than one basin, the estimates of the district are divided according to the geographical area of intersections with sub-basins.

4. Results and discussion

4.1. Snapshot of Water Use Accounts: 2009 - 2011

Of the TRWR of 552 Bm^3/year (Table 1), the potentially utilizable water resources (PUWR) from surface water and groundwater in India and Bangladesh riparian regions is estimated to be 74% (or about 408 Bm^3/year) (Figure 2, first bar). PUWR includes 266 Bm^3/year of surface water and 142 Bm^3/year of groundwater (80% of the natural recharge).

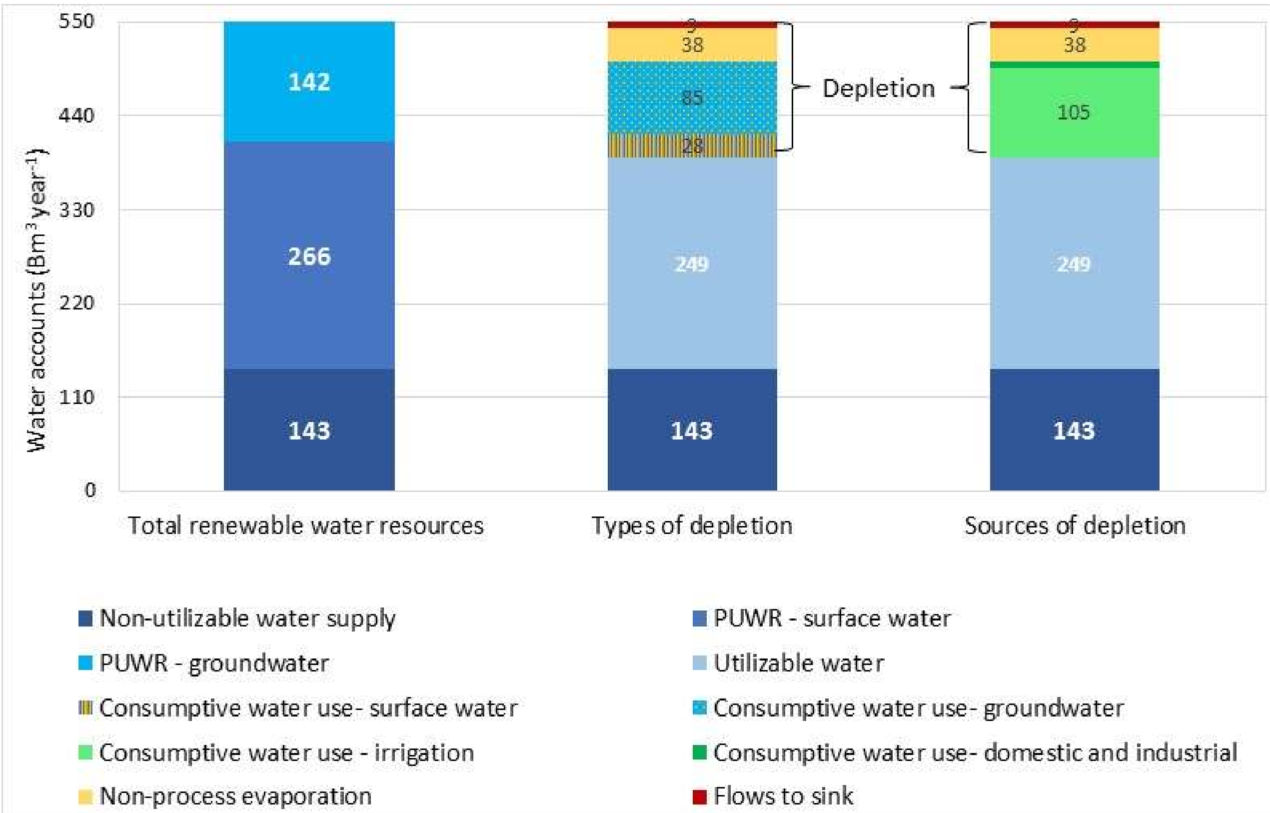

Figure 2. Water use accounts in the Ganges River Basin

Sources: Utilizable surface water, groundwater and non-utilizable water figures are from GoI 1999. Other water accounting figures are authors' estimates

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

- Only 39% (or about 160 Bm^3/~~per~~ year of PUWR was depleted in 2009/2011.
- Process CWU accounts for 72% of the overall depletion, while non-process ET accounts for 22% and flows to sinks account for 6% (Figure 2, second bar).
- Of the process CWU, 75% and 25% are from groundwater and surface water, respectively (Figure 2, second bar).

- Irrigation accounts for 93%, and the domestic and industrial sectors account for 3% and 4%, respectively, of the process CWU (Figure 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 (27%) 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 a ~~enormous~~ potential for increasing water-use efficiency of surface water withdrawals in the Basin. In addition, only 57% of the utilizable groundwater resources are 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, provided that freshwater are available for mixing. 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 eco-systems services ~~ESS~~ and requirements for 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 additionally 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 (Figure 3[a]). This is evidenced by the fact that the average flow at the Harding Bridge in Bangladesh (just below the Indian border) was 347 Bm^3/ ~~per~~ year during 1973-2009, which is two-thirds of the TRWR of the Indian portion of the basin. From Figure 3(a), we observe the range of dependable stream flows as given below:

- At the Harding Brindge, one can expect a discharge of at least 304 Bm^3/ per year 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/ per year.
- In an extreme drought with an average return period of 10 years, the flow is 271 Bm^3/ per year.

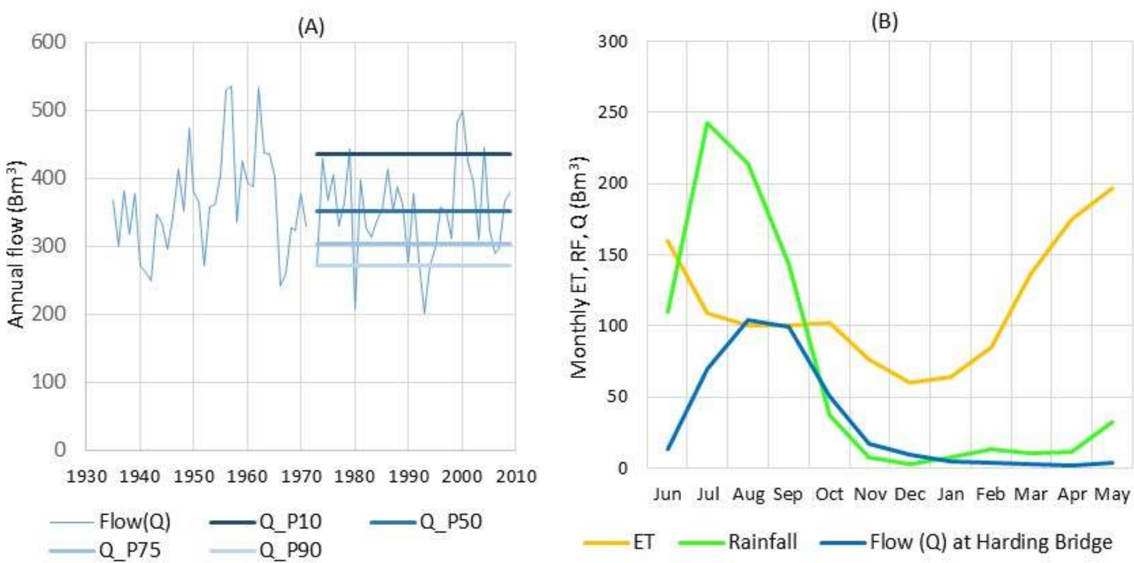

Figure 3. a) River flow (Q)at the Harding Bridge, and b) Average monthly ET, rainfall (RF) and river flow (Q) at Harding Bridge between 1998 and 2008.
Sources: Rainfall (Indian Meteorological Department, ET (*University of East Anglia, Climatic Research Unit, Norwich, UK, 2014*); river flow (Institute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

Figure 3(a) illustrates that a sizable quantity of water flows to the sea, even in an extreme drought year. However, annual aggregate flows illustrated in Figure 3(a) 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 (Figure 3[b]). Groundwater as baseflowbase flow 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 environmental flows. The SSS replenished through monsoon runoff can only increase the dry season environmental flows..

Between 2009 and 2011, the three major sectors (agriculture, domestic and industry) depleted about 150 Bm^3 per year as process and non-process CWU (Figure 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, 2014) 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.

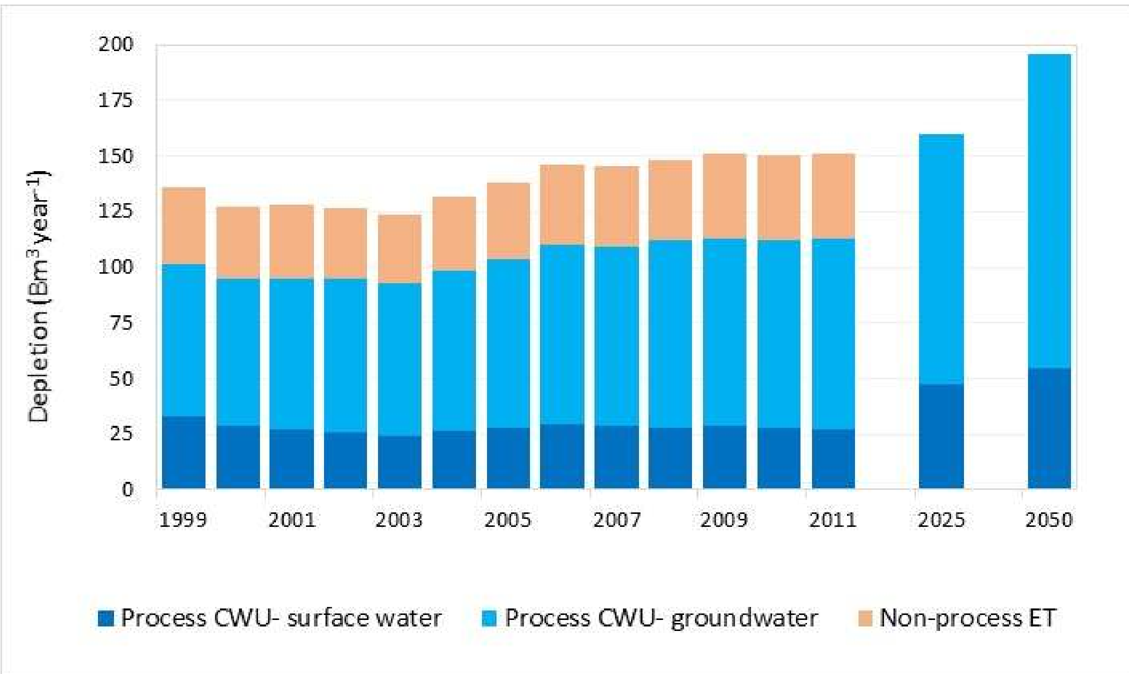

Figure 4. Water use in the Ganges River Basin- past trends and projections.
Source: Trends (1999-2011) are author's estimates. The CWU projections are based on Amarasinghe et al., 2007 and 2014.

Aggregate annual figures also hide large intra-annual variation of irrigation CWU (Figure 5). The process CWU is highest in the *Kharif* season (wet season), but rainfall 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 85 Bm^3 of CWU (64 Bm^3 and 21 Bm^3 from groundwater and surface water, respectively), compared to an average flow of 44 Bm^3 in the river during this period.

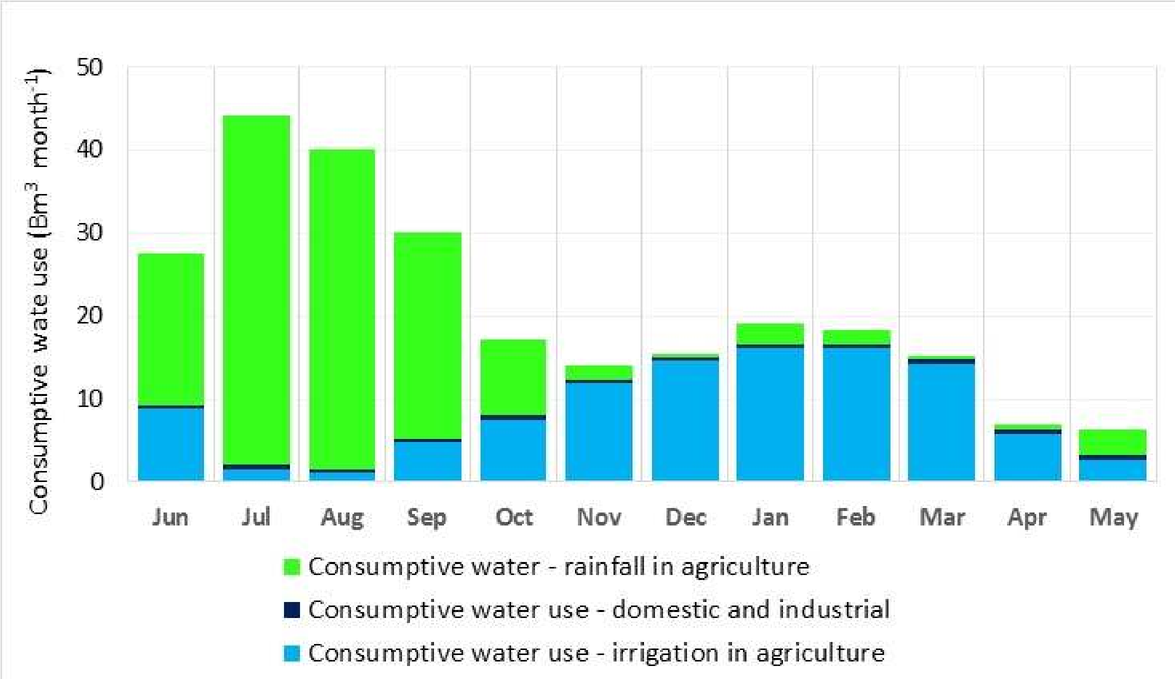

Figure 5. Average monthly CWU between 1999 and 2011.

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, ,another 85 Bm^3 would be needed by 2050 for meeting the irrigation CWU alone in India and Bangladesh riparian regions. If past water-use patterns are an indicators of future use, much of this additional demand will occur in the non-monsoon period, and that also mostly from groundwater irrigation.

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 in India 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, are 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/year. The cumulative totals of the subsequent blue cross-sections show EF estimates for EMCs Eto A, i.e., EF estimate for EMC E is 79 (= 63 + 16) Bm^3/year; EMC D is 105 (= 79 + 26) Bm^3/year; EMC C is 152 (= 105 + 47) Bm^3/year; EMC B is 231 (= 152 + 79) Bm^3/year; and EMC A is 357 (= 231 + 126) Bm^3/year.

The two line graphs in Figure 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, are barely adequate to meet the annual EF requirement of EMC A. And in e~~-E~~very one out of 4 years, t~~. T~~he 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/year. In such an eventuality, the river flow will often be less than the EFs for EMC B.

Figure 6. ET and EF estimates for different e~~E~~nvironmental m~~M~~anagement classes (EMCs)~~Cs~~.

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, and EMC's A and B are realistically not possible to maintain with the present level of development. The present average runoff of more than 340 Bm^3/year is adequate to meet the EF of EMC C of ~~(~~152 Bm^3/year~~)~~ ~~falls under committed flows~~ , and the additional process CWU water demand of about 85 Bm^3/year projected for 2050 ~~(of about 85 Bm^3)~~
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.

In fact, strict maintenance of EF, and also the return flows of additional irrigation from the SSS can increase the dry-season river flows, especially in the downstream region of the Basin. Thus, the additional SSS has the potential to benefit the downstream region of the Basin, such as Bangladesh riparian region, by way of both mitigating floods in the monsoon period and increasing water supply in the dry period.

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 *Rabi* and summer (hot weather) seasons. This can be illustrated by the irrigated and cropped areas (Figure 7) and monthly CWU (Figure 5).

In the *Kharif* season of the Indian riparian region, 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. In the Bangladesh riparian region, very little irrigation is required in the Aus and Aman seasons (about 20 mm), whereas the irrigation CWU is substantially higher in the Boro season (about 383 mm). This shows that the additional irrigated area in the *Rabi* and Boro seasons in India and Bangladesh respectively 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 have the potential for creating higher SSS.

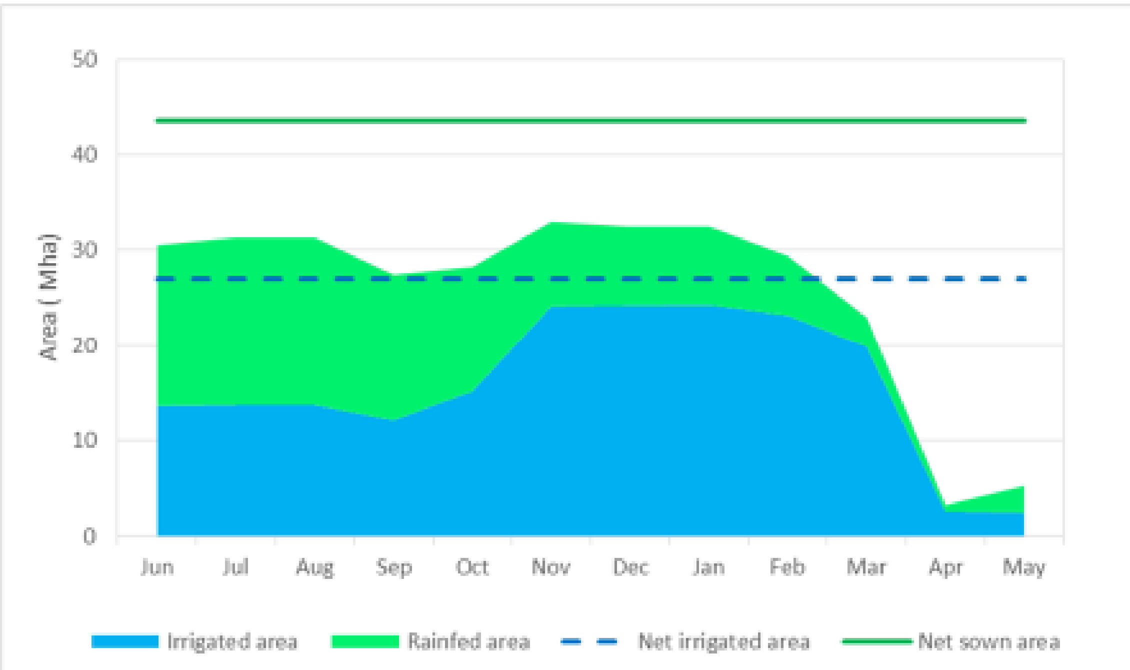

Figure 7. Monthly actual and net irrigated and cropped areas in the Ganges River Basin (2008-2011).

We consider two scenarios to assess the potential for SSS 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 in the Indian region, and Aman and Boro in the Bangladesh riparian region. Here, groundwater pumping will be increased only to bridge the gap between actual irrigated area and the irrigable area, i.e., the net irrigated area.
- Scenario 2 assesses the potential for increasing the gross cropped area in the *Rabi* and hot weather seasons in the Indian region and Boro and Aman seasons in the Bangladesh regions. Here,

groundwater pumping will be increased to bridge the gap between actual irrigated area and the actual cropped area.~~and net sown area~~.

The highest potential for expanding irrigated area exists in the lower Yamuna Sub-basin, where the maximum irrigated and cropped areas of 3.64 Mha 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 lower Yamuna 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 (Table 3, columns C8, C9)~~-~~. Therefore, the additional irrigable area of 4.04 Mha could account for 7.8 Bm^3/year ~~-~~of groundwater CWU (Table 4, column C1).
- 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 (Table 3, columns C10, C11). This additional area could account for another 18.7 Bm^3/year of groundwater CWU (Table 4, column C2).

~~.~~

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~~ ~~S~~Similar potential exists for such an increase between April and May. This has the potential to increase 4.6 Bm^3 to 15.1 Bm^3/year of groundwater irrigation CWU.

Similarly, the Ramganga sub-basin in the upstream has the potential to increase -2.5 Bm^3 to 3.2 Bm^3/year of CWU 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.

Bangladesh riparian region in the downstream of Ganges has a similar situation to that of Ramganga. Although, this region has high groundwater irrigated area and CWU, it has the potential to increase irrigated area by 1.7 to 4.4 Mha. Much of this potential increase in area is in the Aman season (Table 3).

However, due to higher irrigation requirement, much of the potential increase in irrigation CWU is in the Boro season. Overall, this region has the potential to increase irrigation CWU up to 4.8 Bm^3/year.

Table 3. Scenarios of potential increase in irrigated area of the sub-basins in the Ganges

	Sub-Basin	Net irrigated area (Mha)	Maximum monthly irrigated area (Mha)			Maximum monthly cropped area (Mha)			Potential increase in irrigated area[3] (Mha)			
									Scenario 1		Scenario 2	
			Jun-Oct	Nov-Mar	Apr-May	Jun-Oct	Nov-Mar	Apr-May	Nov-Mar	Apr-May	Nov-Mar	Apr-May
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
1	Above Ramganga Confluence	1.35	0.80	1.35	0.36	1.22	1.51	0.37	0.00	0.99	0.16	1.15
2	Banas	0.99	0.48	0.99	0.00	1.71	1.64	0.01	0.00	0.98	0.72	1.70
3	Bhagirathi and others[1]	1.78	1.70	0.50	0.42	4.75	2.12	0.92	1.27	1.35	4.24	4.32
4	Chambal Lower	0.41	0.22	0.39	0.00	0.40	0.53	0.00	0.02	0.41	0.14	0.53
5	Chambal Upper	1.08	0.50	0.92	0.01	1.57	1.38	0.01	0.16	1.07	0.65	1.57
6	Damodar[1]	0.96	0.96	0.10	0.10	2.89	0.96	0.20	0.86	0.86	2.79	2.79
7	Gandak and others	1.55	1.00	1.18	0.08	1.91	1.63	0.24	0.37	1.47	0.73	1.83
8	Ghaghara	3.01	1.76	2.95	0.49	3.35	3.50	0.68	0.06	2.52	0.55	3.01
9	Ghaghara and Gomti Confluence	1.39	1.10	1.10	0.04	1.29	1.28	0.05	0.29	1.35	0.19	1.25
10	Gomti	1.48	1.03	1.36	0.16	1.21	1.52	0.19	0.11	1.32	0.15	1.36
11	Kali Sindh	1.96	1.04	1.50	0.01	2.71	2.21	0.01	0.46	1.95	1.21	2.70
12	Kosi	0.70	0.45	0.65	0.10	1.05	0.87	0.23	0.05	0.60	0.40	0.94
13	Ramganga	1.68	1.36	1.68	0.42	1.60	1.84	0.44	0.00	1.25	0.16	1.42
14	Son	0.74	0.43	0.51	0.02	2.69	1.35	0.07	0.23	0.72	2.19	2.68
15	Tons	0.32	0.14	0.28	0.00	0.59	0.65	0.00	0.03	0.32	0.37	0.65
16	Upstream of Gomti	1.95	1.15	1.95	0.23	1.55	2.17	0.24	0.00	1.72	0.21	1.93
17	Yamuna Lower	3.86	1.71	3.64	0.05	4.53	6.19	0.05	0.22	3.82	2.55	6.15
18	Yamuna Middle	2.14	1.04	2.14	0.06	1.44	2.46	0.06	0.00	2.08	0.32	2.40
19	Yamuna Upper	2.76	1.65	2.76	0.52	2.10	3.23	0.54	0.00	2.24	0.47	2.71
20	Bangladesh[2]	2.92	0.68	1.20	2.92	3.97	4.24	3.50	1.72	0.00	3.05	1.32
	Total	33.03	19.20	27.15	5.99	42.53	41.28	7.81	5.85	27.02	21.25	42.41

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, March-April

[2-] The periods for Bangladesh are May-August, August-November and November-April coincide with Aus, Aman and Boro seasons.

[3-] C8=C1-C3; C9=C1-C4; C10=Max(C5,C6)-C3; C11= Max(C5,C6)-C4.

Table 4. Scenarios of potential increase in irrigated CWU of the sub-basins in the Ganges

	Sub-basin	Potential increase in ~~ground water~~ irrigation CWU in Nov-May (Bm³/year)		Realizable potential unmet demand in Nov-May (Bm³/year)		Ground water resources in 2009 (Bm³/year)	75% probability dependable surface runoff (Bm³/year)	Ground water CWU (Bm³/year)	Groundwater CWU in 2009 - % of groundwater resources	Total CWU (Bm³/year)	Total CWU in 2009 - % of total resources
		Scenario 1	Scenario 2	Scenario 1	Scenario 2						
		C1	C2	C3	C4	C5~~3~~	C6~~4~~	C7~~5~~	C8~~6~~	C9~~7~~	C10~~8~~
1	Above Ramganga Confluence	1.7	2.4	1.7	1.7	5.5	5.2	5.6	108	6.4	59
2	Banas	1.2	4.1	0.0	0.0	3.5	2.6	3.0	117	3.4	56
3	Bhagirathi and others 1	4.6	15.1	4.6	15.1	-	21.7	2.7	12	4.5	21
4	Chambal Lower	0.8	1.4	0.0	0.0	1.2	1.3	0.8	63	1.3	50
5	Chambal Upper	2.6	5.1	2.6	2.6	6.6	4	3.1	77	3.7	35
6	Damodar1	3.7	12.1	3.7	12.1	-	9.7	1.1	12	2.2	22
7	Gandak and others	5.2	7.2	5.2	7.2	11.8	13	3.4	26	4.8	19
8	Ghaghara	5.1	7.5	5.1	7.5	23.3	20.5	10.5	51	12.3	28
9	Ghaghara and Gomti Confluence	3.4	2.9	2.9	3.4	3.3	7.7	2.9	37	5.1	47
10	Gomti	2.6	2.8	2.6	2.8	9.8	8.5	4.8	56	6.6	36
11	Kali Sindh	3.9	7.1	3.9	3.9	10.5	5.9	4.0	67	5.9	36
12	Kosi	1.0	2.4	1.0	2.4	6.8	6.3	1.8	28	2.2	17
13	Ramganga	2.5	3.3	2.5	2.5	10.1	7.8	7.8	100	8.8	49
14	Son	1.9	11.3	1.9	11.3	14.1	9.3	1.1	12	2.5	11
15	Tons	0.7	2.3	0.7	2.3	5.2	1.6	0.7	42	1.2	17
16	Upstream of Gomti	2.9	3.9	2.9	2.9	5.7	9.7	6.8	71	9.0	59
17	Yamuna Lower	7.8	18.7	0.0	0.0	15.2	16.9	7.6	45	12.5	39
18	Yamuna Middle	3.4	4.7	0.0	0.0	2.1	5.4	6.3	116	7.5	101
19	Yamuna Upper	3.7	5.6	3.7	5.6	4.5	8.5	8.9	105	12.6	97
20	Bangladesh	0.3	4.8	0.3	0.3	22	5.5	4.8	87	9.3	34
	Total	59.0	124.7	45.3	83.6	161	171	87.7	51	121.8	37

Source: 75% probability dependable surface runoff is from Muthuwatta et al., (2015). Others are author's estimation

Table 4 shows that all sub-basins in the Ganges River Basin have the potential to increase irrigation CWU between 59 and 124 Bm^3/year of groundwater under scenarios and 1 and 2, respectively. . However, realization of this full potential is difficult given the current water use and availability in different sub-basins. Figure 8A shows the present level of groundwater exploitation (groundwater CWU as a % of groundwater resources), and Figure 8B indicate the potential for increasing process CWU to create SSS in the sub-basin.

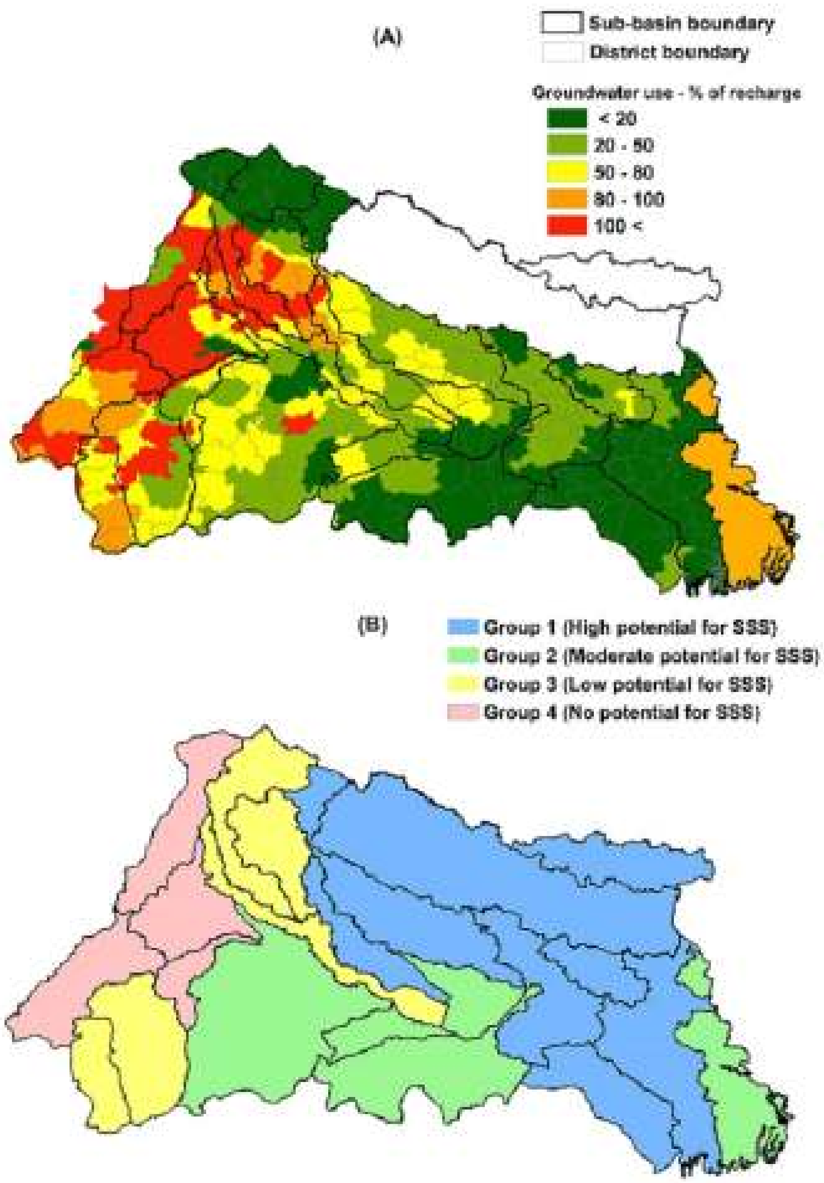

Figure 8: A). Groundwater exploitation at present, and B). theThe potential for increasing SSS in the Ganges Basin

The middle and upper Yamuna basins have already exhausted their total water resources (Figure 8A), where even the process CWU are 101 and 97% of the total water resources respectively (Table 4). Any further increase in process CWU would only exacerbate the unsustainable water use. The middle and upper Yamuna sub-basins have no potential for PDRP and increasing SSS. The Banas and lower Chambal also have high CWU relative to their total water resources, and the potential increases in process CWU would be significantly higher than their available water resources. These four sub-basins have very little or no potential for PDRP and increasing SSS (Figure 4B red color).

The sub-basins: above Ramganga confluence, Ramganga, upper Chambal, Kali Sindh and upstream of Gomti confluence and the Bangladesh riparian region have substantially high groundwater use. These sub-basins have very little uncommitted groundwater resources for further increase in groundwater CWU. Any further increase in groundwater CWU even under Scenario 1 is possible only with substantial recharge of the aquifers during the monsoon period. These sub-basins have low potential for PDRP and creating SSS (Figure 4B yellow color).

The lower Yamuna, Son, Ghaghara, between Ghaghara and Gomti confluence, and Tons sub-basins have sufficient uncommitted groundwater resources to meet the increased CWU under Scenario 1 (Table 4), but not sufficient under Scenario 2~~B~~. However, the un-committed total water resources in these basins can meet the increased irrigation CWU under both scenarios. The potential for increasing groundwater CWU under scenario 2 depends on the ability of managed aquifer recharge programs to capture the uncommitted monsoon surface runoff. These basins have a moderate potential for PDRP and increasing SSS (Figure 4B green color).

In the other sub-basins, the present levels of groundwater development are very low. They have sufficient un-committed groundwater resources to meet the increased irrigation CWU under both scenarios. In these basins, natural interactions between groundwater and surface water can recharge the SSS created by the depletion of groundwater resources. These basins have the highest potential for PDRP and increasing SSS (Figure 4B blue color). Although we have not considered the Nepal for this analysis, given their vast water resources and very low irrigation CWU at present (FAO 2015), it is a natural candidate for high potential category.

Given the constraints of water surface and groundwater availability and high water use at present in the four groups, only 45-84 Bm^3/year can be potentially realizable as SSS for meeting the un-met demand under the two scenarios. 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 dis-benefits.
- Magnitude of the current monsoon runoff in sub-basins, which is available for recharging SSS.
- Ability to recharge SSS through monsoon runoff, especially during 3-4 months of the monsoon season, using natural or artificial interaction of surface water and groundwater. This recharge is essential for sustainable groundwater use.

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

- Properties of the soil, and the ‘crop holidays’ ~~-~~(i.e., a temporary fallow ~~a~~ periods ~~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

A potential solution to Ganges water problems is to create additional SSS by means of reviving the GWM. One of the necessary conditions for reviving the GWM is ensuring there is unmet water demand. This analysis finds that between 59 and 124 Bm^3/year 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.

However, given the current water use and availability patterns, all that potential cannot be actually realized in most sub-basins of the Ganges. While some basins (Gandak, Ghaghara, Gomti, Kosi, Bhagirathi, Damodar and Nepal) have adequate groundwater resources to fully realize the irrigation potential, some other basins (middle Yamuna, upper Yamuna, Banas and lower Chambal) have little or no water resources to realize the estimated irrigation potential. Few sub-basins (above Ramganga confluence, Ramganga, upper Chambal, Kali Sindh and upstream of Gomti confluence and the Bangladesh riparian region have low potential and others (lower Yamuna, Son, Ghaghara, between Ghaghara and Gomti confluence, and Tons) have moderate potential for increasing the irrigation PDRP and creating SSS. Overall, it is feasible to realize between 45 and 84 Bm^3/year of SSS to meet the potential unmet demand.

One of the most challenging aspect of reviving the GWM is to maintain the required flows during the low-flow period. Because EF is not part of the current water management plans, many stretches of the river already have an unacceptable levels of low flows in the dry season. This may require substantial changes to water releases from the reservoirs upstream 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 base flows during the non-monsoon period.

However, where and to what extent the SSS can be created through PDRP without affecting the dry-season flows in the downstream riparian regions require further hydrogeological, socio-economic and institutional analyses. Being a transboundary river, it is important to assess ways of strict maintenance of dry-season EF and other water requirements of the downstream riparian region, especially Bangladesh. Such analysis, which is beyond the scope of this paper, requires the knowledge of surface runoff of smaller watershed, the extent and spatial distribution of groundwater availability and depletion, EF during the dry periods, capacity to recharge through natural or artificial mean during short periods of wet spells in the monsoon, and the socio-economic cost and benefits and tradeoff

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Author contributions

Upali A. Amarasinghe and Lal Mutuwatte are ~~is~~ fully responsible for the analysis and writing of this paper. ~~Lal Mutuwatte,~~ Lagudu Surinaidu, and S.K. Jain have provided data and ~~also~~ comments and suggestions during the analysis and write-up. Sumit Anand assisted in ~~is responsible for~~ collecting data and generating ~~the~~ GIS maps.

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