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Reviving the Ganges Water Machine: Potential and Challenges to Meet Increasing Water Demand in the Ganges River Basin ●●●

Upali A. Amarasinghe, Lal Muthuwatta, Vladimir Smakhtin, Lagudu Surinaidu, Rajmohan Natarajan, Pennan Chinnasamy, Krishna Reddy Kakumanu, Sanmugam A. Prathapar, Sharad K. Jain, Narayan C. Ghosh, Surjeet Singh, Anupma Sharma, Sanjay K. Jain, Sudhir Kumar and Manmohan K. Goel



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IWMI Research Report 167

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Front cover (clockwise from top left): (a) Yamuna River, India, (b) surface water irrigation (minor off-take from a distributary) (in Uttar Pradesh), (c) groundwater irrigation (in Kolkata), and (d) a farmer irrigating his field (in Kolkata) in the Ganges River Basin (*photos*: Nitasha Nair, IWMI).

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The National Institute of Hydrology, Roorkee, Uttarakhand, India, the national partner of this project, conducted the modelling studies in the Ramganga sub-basin of the Ganges in collaboration with the International Water Management Institute (IWMI).

Donors

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Acronyms

BCR	Benefit-cost ratio
CBA	Cost-benefit analysis
CWU	Consumptive water use
EF	Environmental flow
EMC	Environmental management class
ET	Evapotranspiration
ETP	Potential evapotranspiration
EWP	Economic water productivity
GCA	Gross cropped area
GDP	Gross domestic product
GIA	Gross irrigated area
GRB	Ganges River Basin
GWIA	Groundwater-irrigated area
GWM	Ganges Water Machine
IRCWU	Consumptive water use from irrigation
IRR	Internal rate of return
IRWR	Internally renewable water resources
MAR	Managed aquifer recharge
NIA	Net irrigated area
NRCS	Natural Resources Conservation Service, United States Department of Agriculture
NSA	Net sown area
O&M	Operation and maintenance
PUWR	Potentially utilizable water resources
RFCWU	Consumptive water use from rainfall
SSS	Subsurface storage
SWAT	Soil and Water Assessment Tool
TCWU	Total consumptive water use
TRWR	Total renewable water resources
USDA	United States Department of Agriculture

Summary

The Ganges River Basin (GRB) has abundant water resources, but the seasonal monsoon causes a mismatch in water supply and demand. This mismatch creates severe water-related challenges for the 600+ million people living in the basin, the rapidly growing economy and the environment. Addressing these challenges, which are only increasing, depends on how people manage the basin's groundwater resources. At present, more than 75% of the process depletion (evapotranspiration) from the irrigation, domestic and industrial sectors in the GRB is from groundwater withdrawals. The reliance on groundwater in the basin will increase further due to limited prospects for development of additional surface water storages. This report assesses the potential of the Ganges Water Machine (GWM), a concept proposed 40 years ago, to meet the increasing water demand through groundwater, and mitigate the impacts of floods and droughts. The GWM provides additional subsurface storage (SSS) through the accelerated use of groundwater prior to the onset of the monsoon season, and subsequent recharging of this SSS through monsoon surface runoff. There is a potential unmet water demand of 59-125 Bm³/year under two different scenarios of irrigation water

use. However, the realizable potential is only 45-84 Bm³ due to supply constraints. The realizable potential is high only in seven sub-basins in the northern and eastern parts of the GRB, is moderate to low in 11 sub-basins in the middle part, and there is little or no potential in four sub-basins in the western part. A preliminary ex-ante cost-benefit analysis, which captures the potential gains and losses after implementing a project, shows that the GWM is a financially viable intervention with a benefit to cost ratio of over 2.3. However, actual realization of its potential depends on many other hydrological and socioeconomic factors. The report shows that there is potential to enhance the subsurface storage by managed aquifer recharge during the monsoon season. It illustrates prospects of using solar energy for groundwater pumping, which is financially more viable than using diesel as practiced in many areas at present. The report further explores the limitations associated with water quality issues for pumping and recharge in the GRB, and discusses other related challenges, including availability of land for recharge structures and people's willingness to increase the cropping intensity beyond the present level.

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Introduction

The Ganges River Basin (GRB) covers a land area of 1.086 million square kilometers (km²) and cuts across four south Asian countries, with India, Nepal, Bangladesh and China taking up 79%, 14%, 4% and 3% of this area, respectively (Figure 1). Mean annual river flow volume of the entire basin is estimated to be in the order of over 550 billion cubic meters (Bm³).

The GRB is home to 8.3% of the world's 7.3 billion population, and is one of the densest poverty hot spots in the entire world. There were 158 million low-income people, accounting for 26% of the basin population in 2011. More than 450 million (or 80%) of the basin population are under multi-dimensional poverty conditions (Amarasinghe et al. 2016), which means that they lack adequate education, health and standard of living (Alkire and Santos 2011). The majority of the basin population lives in rural areas, and depends on agriculture for food and livelihood security (Sharma et al. 2010), which, in turn, significantly depend on the availability of, and access to, water in the Ganges River.

Apart from irrigation, river water is an important source for fisheries (Payne and Temple 1996) and navigation, extending a stretch of 1,500 km. With an installed capacity of over 2,000 megawatts, hydropower generation is another major service that the river provides. Moreover, the Ganges River flow is sacred to Hindu devotees, and holy pilgrimage sites are dotted all across the basin.

Recurring floods and droughts associated with climate variability are common in the landscape and waterscape of the GRB. Floods in the monsoon season (June to October) and prolonged dry periods in the non-monsoon season (November to May) are recurrent phenomena. They affect thousands of people and livestock, and damage crops and properties worth millions of dollars (Gol 2015).

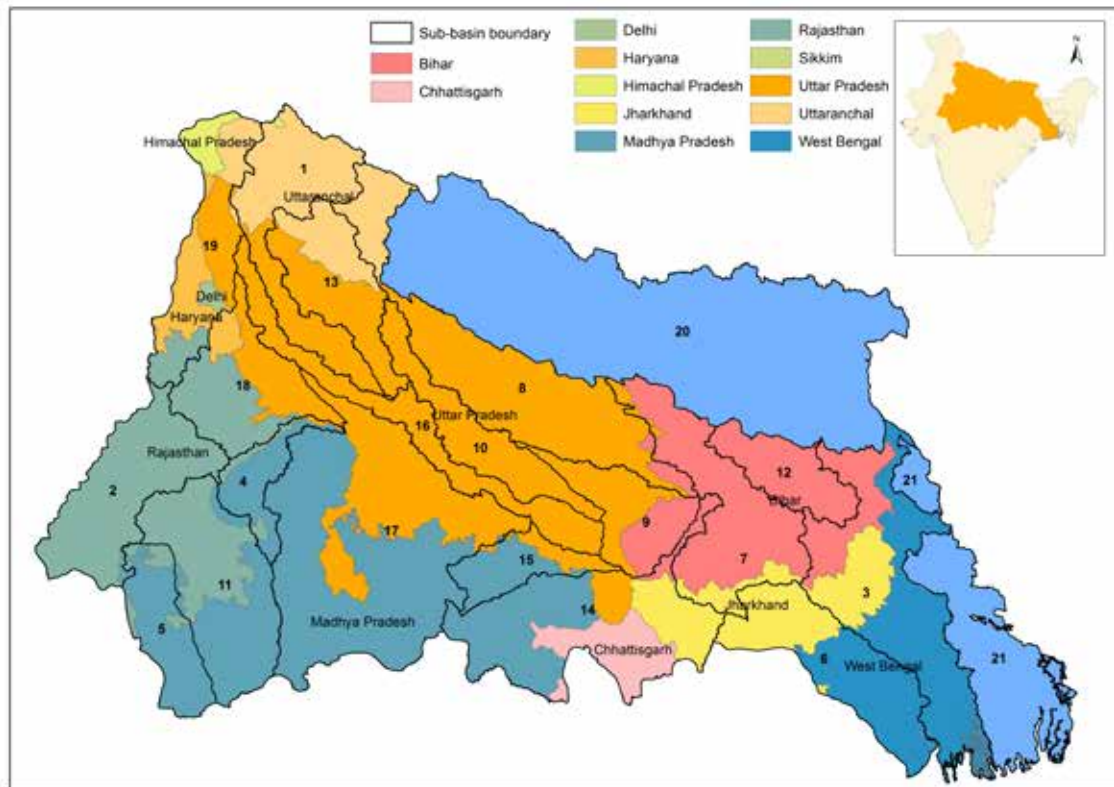
Climate change exacerbates these hazards (Hosterman et al. 2012; Sharmila et al. 2015). Due to various developments in the basin, there is virtually no water in some stretches of the river during the low-flow period (Khan et al. 2014; Chinnasamy 2016), and bringing the river flow back to acceptable levels is the emphasis of political and policy discourses, and research programs (NMCG 2014; O'Keeffe et al. 2012).

Adding the important environmental flow (EF) dimension to already complex water management in the GRB may increase the unmet demand from other sectors (Sapkota et al. 2013). A substantial yield gap also exists in the major cropping system of rice and wheat in the basin (Aggarwal et al. 2000). According to several projections, the irrigated area of the basin will have to be increased by another 10 to 15 million hectares (Mha) from the present level to meet food and livelihood security in the next two to three decades (Molden 2007; Shrestha et al. 2015). Thus, it is clear that there is already substantial unmet demand in the basin, which is increasing

and needs to be met as soon as possible. With the large intra-annual flow variation, increasing storage capacity is the usual water management

option that comes to mind. However, the GRB has limited potential for further expansion of surface storage (Jeuland et al. 2013).

FIGURE 1. The Ganges River Basin showing state and country boundaries, and the hydrological sub-basins used in this study.



Note: Numbers (and names) of the sub-basins in the map correspond to those in column 1 in Tables 3, 4 and 5.

The 'Ganges Water Machine' (GWM) is a concept introduced in the mid-1970s by Revelle and Lakshminarayana (1975) to enhance water storage. It is a departure from traditional methods of storing water in surface reservoirs and tanks. In summary, it entails the following:

- Pumping water before the monsoon for irrigation and use in other sectors, thereby creating an additional subsurface storage (SSS) in the basin.
- Using carefully planned recharge structures to recharge SSS from the monsoon runoff. The cycle of pump-recharge-pump increases storage for runoff water, which helps to mitigate the impacts of floods and droughts.

The GWM envisaged capturing about 115 Bm³ of monsoon runoff per year in SSS, and using this additional water to irrigate about 38 Mha of cropland. However, over the last 40 years, the estimate of gross irrigated area (GIA) has already been realized (Amarasinghe et al. 2007). As a result, some areas are experiencing falling groundwater tables (Chinnasamy 2016).

The GWM concept has never been implemented at scale, but the idea has never died either. With increasing water shortages in the basin, which were foreseen even 40 years ago, the concept needs to be revisited, and prospects and limits of its practical implementation need to be examined in detail in the current physical and socioeconomic context of the GRB. This report analyzes the following:

- Dynamics of the key drivers of the GWM - floods, droughts, surface storages and groundwater development - over the last four decades.
- Potential of the GWM to increase SSS for addressing increasing water shortages, by conducting a water accounting analysis at sub-basin level.
- Ex-ante financial benefits and costs of the potential of the GWM.
- Issues and challenges in implementing the GWM in the basin under the current socio-environmental settings.

Data and Methods

The main drivers of the GWM are floods and droughts (with associated damage), and groundwater development (with associated costs and benefits). A large body of secondary data available at the subnational level (districts or states) in the public domain are used to examine these trends. These data sources include the following:

- India
 - District-level population data (1971, 1981, 1991, 2001 and 2011) - publications of population censuses (<http://censusindia.gov.in/>).
 - District-level average monthly potential evapotranspiration (ETP) and rainfall estimates from 1971 to 2011 are from the Climate Research Unit, University of East Anglia, UK, and India Meteorological Department, respectively.
 - District-level agricultural statistics (area, production, cropping calendar): data and various issues of 'Agricultural Statistics at a Glance' published on the website of the Directorate of Economics and Statistics, Department of Agriculture and Corporation, Ministry of Agriculture, Government of India, New Delhi, India (<http://lus.dacnet.nic.in/>).
 - Basin-level water availability and state-level estimates of flood damage in India - water-related publications of the Central Water Commission, India (<http://www.cwc.nic.in>).
- Bangladesh: Agricultural statistics from various publications of the Bangladesh Bureau of Statistics, including the *Yearbook of Agricultural Statistics of Bangladesh* (<http://www.bbs.gov.bd>).
- Nepal: Agricultural and water-related statistics are from the FAOSTAT (<http://faostat.fao.org/>) and AQUASTAT (<http://www.fao.org/nr/water/aquastat/main/index.stm>) databases of the Food and Agriculture Organization of the United Nations (FAO).
- Crop coefficients and crop growth stages of all countries are obtained from the AQUASTAT database (http://www.fao.org/nr/water/aquastat/water_use_agr/Annex1.pdf) and Allen et al. (1998).

The analysis considers 21 sub-basins of the GRB: 19 sub-basins identified by the Central Water Commission, India (the main government agency responsible for national water resources development and management), and Nepal and the Ganges part of Bangladesh (Figure 1). Most of the data mentioned above are available at the administrative divisional level for India (districts and states) and Bangladesh (districts). Some of the administrative boundaries cut across the sub-basin boundaries. Therefore, the basin- and

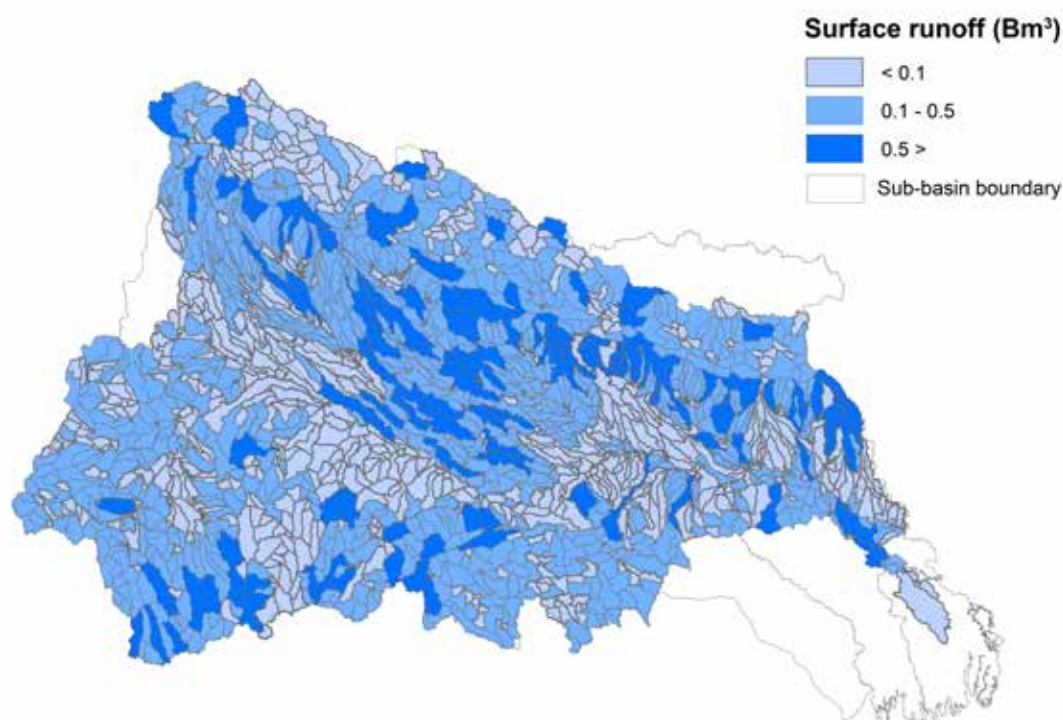
sub-basin-level estimates of various variables are derived by proportional allocation of the district-level totals to the geographical area of the districts included in the basins or sub-basins.

To assess the potential of the GWM, the report conducts a partial water accounting of the Ganges sub-basins. This partial water accounting (Molden 1997) reflects the present level of water resources development in the GRB and its sub-basins, including renewable water resources (surface water and groundwater) and water depleted through evapotranspiration (ET). ET includes the process consumptive water use from irrigation (IRCWU), domestic and industrial withdrawals, and the non-process ET from reservoirs, homesteads and bare surfaces, etc. Other parts of the water accounts are flows to sinks (flows of which the quality of water

has deteriorated so much that it cannot be used any further), committed flows (environmental flows, inter-basin transfers) and uncommitted flows (flows to the sea).

There are no official estimates of the surface water resources available/accessible to the sub-basins of the GRB. There have been several modelling efforts to simulate the hydrology of the GRB with varied spatial resolution and accuracy (Jain et al. 2016). However, detailed results of most of these modelling exercises are not available in the public domain. This report uses the simulations of surface runoff (excluding groundwater) provided by Muthuwatta et al. (2015), who applied a widely used Soil and Water Assessment Tool (SWAT) model to the GRB by splitting it into 1,684 sub-catchments (Figure 2).

FIGURE 2. A map of simulated surface runoff for 1,684 sub-catchments of the GRB.



Source: Muthuwatta et al. 2015.

Notes: The GRB was delineated using 3,000 ha as a minimum area threshold that resulted in 1,684 catchments. The model was initially developed to study streamflow entering Bangladesh, and the overall GRB boundary was subsequently revisited. Therefore, the spatial domain of this Ganges SWAT model does not entirely cover the entire basin area. Also, due to limited observed flow data, the model was calibrated only at a few locations in Nepal, and at Farakka Barrage. It is naturally possible to improve the accuracy of the analyses described in this report, when/if other simulations of the hydrology of the GRB (accepted or perceived as being more accurate) are available.

SWAT is a semi-distributed, hydrological model developed by the Agricultural Research Service of the United States Department of Agriculture (USDA) over the last 30 years, and is available in the public domain (Arnold et al. 1998; Gassman et al. 2007). The model describes all the hydrological processes in the basin, and allows for detailed representation of spatial heterogeneity of soils, land use and topography of the basin. The estimate of surface runoff of the sub-basins is the sum of surface runoff from the small catchments within each sub-basin.

The process ET from irrigation, the largest component of depletion, is the IRCWU of crops. We estimate the monthly IRCWU in four crop

growth periods (initial, development, middle and late) of 31 different crops or crop groups across the districts in sub-basins over the period from 1998 to 2011. 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, linseed, soybean, 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. The total consumptive water use (TCWU) of all crops in the j^{th} month can be estimated using equation (1) (Allen et al. 1998).

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

Where: C_k is the crop coefficient of the k^{th} growing period, ETP_j is the potential evapotranspiration of the j^{th} month, and d_{jk} is the number of days of the k^{th} growth period in the j^{th} month.

Consumptive water use from rainfall (RFCWU), which is essentially the effective

rainfall (portion of rainfall stored at the root zone of a crop), is estimated using the USDA Natural Resources Conservation Service (NRCS), formerly Soil Conservation Service (SCS), method (Smith 1992). The RFCWU of the j^{th} month is given in equation (2):

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

Where: RF_j is the rainfall of the j^{th} month. The monthly IRCWU is then estimated as the

difference between TCWU and RFCWU of all crops as shown in equation (3).

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

Following the water accounting analysis, the potential of GWM under present land and water use conditions is estimated. First, the current cropped and irrigated areas are used to estimate the potential for increasing the irrigated areas in the sub-basins. Second, the analysis combines the potential increase in irrigated area with IRCWU to assess the potential unmet water demand. Finally, the study compares this with the

current water accounts to estimate the potentially realizable unmet water demand.

Next, the ex-ante benefits and costs of the realizable potential of the GWM are estimated to assess the net value of output of additional irrigation. First, the economic water productivity of crops (value of crop production per unit of CWU) is estimated. Second, the value of additional crop production using the economic water productivity

is estimated, by assuming that groundwater will meet the additional unmet irrigation demand. Third, the cost of additional crop production is estimated using the cost of production data collected from a sample survey of 600 farm households from the Ramganga sub-basin of the GRB.

The study also estimates the additional benefits to the domestic and industrial sectors by assuming that a small part of the groundwater

recharged under the GWM will benefit these sectors. There are no reliable data to estimate the economic water productivity of the domestic and industrial sectors. Therefore, the study uses the economic water productivity of crop production to estimate the benefits of water use in the domestic and industrial sectors, although, in reality, the net financial benefits could be much higher in these sectors.

The Need

Increasing Flood Damage

The damage caused by floods has increased substantially over the last four decades in the GRB, although the frequency and peaks of flooding show no major change (Figure 3[a], [b]). The high rainfall during the monsoon season generates more than 85% of the total surface runoff of the GRB (Figure 3[a]). For example, the average annual monsoon river flow at the Hardinge Bridge in Bangladesh (just below the Indian border) is about 310 Bm³/year. Annual flows at the Hardinge Bridge are likely to exceed the average annual flow in three out of 5 years, and exceed 250 Bm³ in four out of 5 years. These high river flows cause recurrent flooding in many riparian regions.

Although the likelihood of the incidence of flooding due to high rivers flows (between 250-350 Bm³) shows no major change from pre- to post-1970s, the damage caused to people and property as a result of flooding has increased substantially (Figure 3[b]). The area most affected by flooding is the eastern Ganga region, which includes the state of eastern Uttar Pradesh, Bihar, West Bengal and the Bangladesh riparian region (Chinnasamy 2016; Muthuwatta et al. 2015).

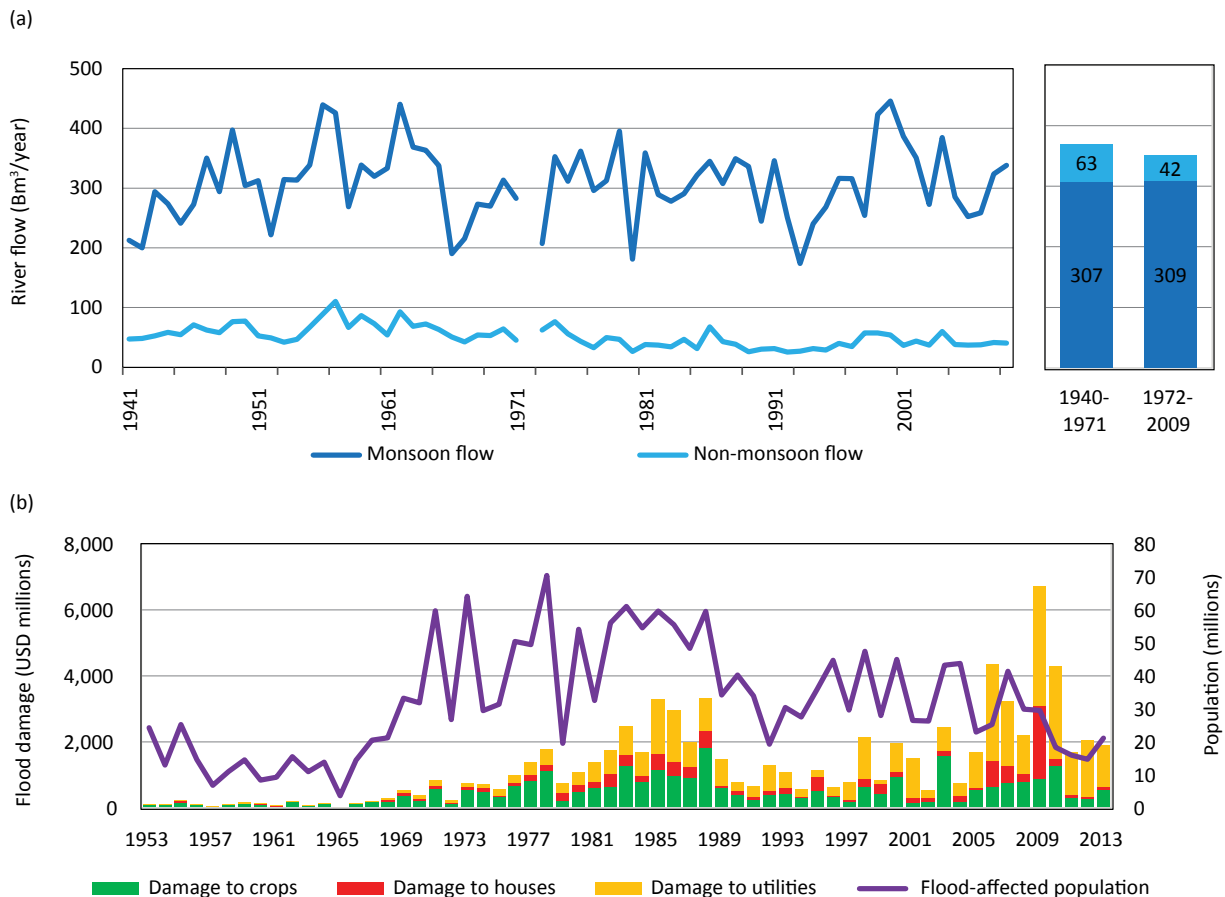
In 2013, floods affected over 13.7 million people in the states of Bihar, Uttar Pradesh, Uttaranchal and West Bengal alone, which was two-thirds of the total flood-affected population in

India in the same year (Gol 2015). These floods also damaged crops, and public and private utilities worth over USD 700 million in the four states, which was about one-third of the total flood damage in India. In comparison, floods caused damages amounting to USD 479 million (at current prices) in the whole of India during the period 1970-1971 (Gol 2015).

Although the projections of rainfall for the GRB are widely divergent, climate change may exacerbate the water-related issues in these regions due to extreme variability of rainfall and associated streamflow. Hosterman et al. (2012) predicted a decrease in annual rainfall, while Sharmila et al. (2015) and Kumar et al. (2011) predicted an increase in monsoon rainfall and longer monsoon seasons. The latter also predicted an increase in dry spells during the monsoon season, implying that the intensity of precipitation in the rainfall events will increase. However, according to Lutz et al. (2014), water availability in the upstream parts of the GRB may increase during the low-flow periods.

While an increase in non-monsoon rainfall may be favorable for the GRB, any increase in monsoon rainfall and resulting floods will be the major issue for the flood-affected riparian regions with rapid population and economic growth. While the total population of Bihar and Uttar Pradesh has increased by 20 and 25%, respectively, between 2000 and 2010, the gross domestic

FIGURE 3. (a) Rainfall and river flow during the monsoon and non-monsoon seasons at the Hardinge Bridge, and (b) damage caused by flooding in India.



Sources: Flow data - Institute of Water Modelling (IWM), Bangladesh; rainfall data - India Meteorological Department; and area affected and damage caused by flooding - GoI 2015.

Note: Floods in the states of Andhra Pradesh and Karnataka contributed to most of the flood damage in 2006, 2009 and 2010.

product (GDP) of both states has increased by over 190%. Given that these two states have close to 50% of the 600 million basin population, recurrent floods, if not managed, will cause further damage.

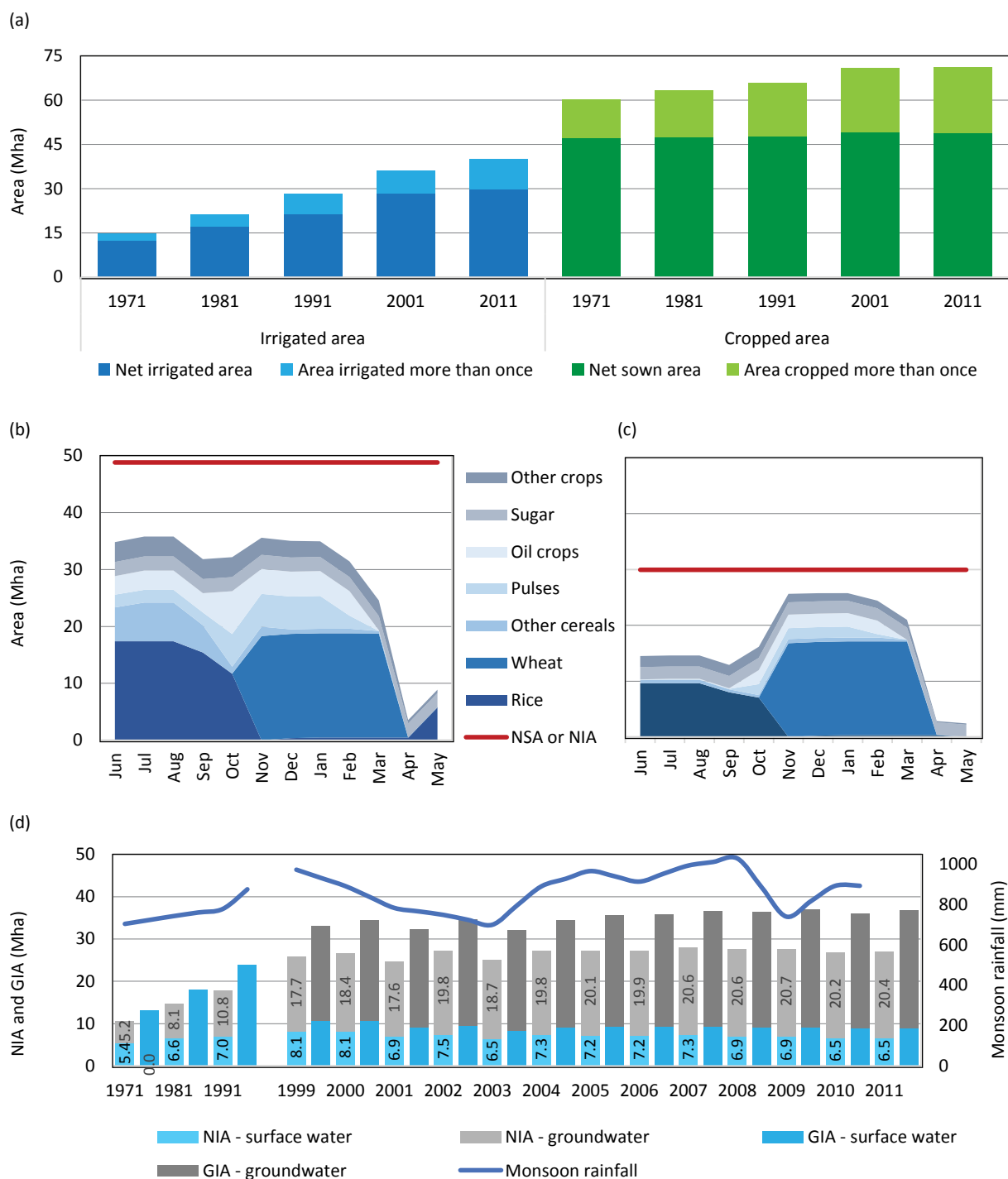
Increasing Drought Damage

Meteorological droughts, which occur due to little or no rainfall during an extended period in the non-monsoon season, are widespread in the GRB. This, along with economic water scarcity (due to insufficient water development), barely allows annual cropping and irrigation intensities to be over 133% and 145%, respectively (Figure 4[a]). Irrigation intensity here is defined as the ratio of

GIA in the three seasons – *Kharif* (June-October), *Rabi* (November-March) and hot weather (April-May) – to the net irrigated area (NIA) in the basin. Although NIA has increased over 140%, irrigation and cropping intensities have only increased from 119% to 134% and 128% to 143%, respectively, over the last four decades.

At present, the Indian riparian region accounts for 90% of the cropped and irrigated areas in the GRB. Low irrigation intensity in this region is primarily due to the smaller area cultivated in the *Rabi* and hot weather seasons. Monsoon rainfall provides much of the crop water requirements in the *Kharif* season; so, the irrigated area is naturally substantially lower than NIA during this season (Figure 4[b]). However, irrigation is critical for both perennial and non-perennial crop production in the *Rabi* and hot weather seasons.

FIGURE 4. (a) Trends in irrigated and cropped areas in the GRB, (b) land-use patterns of different crops, (c) irrigation patterns of different crops, and (d) NIA and GIA from surface water and groundwater, and monsoon rainfall in the Indian riparian region.



Notes: Distribution of GIA from surface water and groundwater is not available before 1999.

NSA – Net sown area.

However, the actual area irrigated during the *Rabi* and hot weather seasons is substantially lower than NIA (Figure 4[c]), which is primarily due to low water availability. Nepal accounts for about 5% of the irrigated area and has similar seasonal irrigation patterns to that of the Indian region.

The Bangladesh riparian region shares about 5% of NIA and GIA, and has a completely different irrigation pattern. In this region, there is hardly any irrigated area in the *Aman* season (equivalent to *Kharif* season in the Indian region), while paddy grown in the *Boro* season from March to May (equivalent to the hot weather season in the Indian region) accounts for a major share of irrigation water use. This helps Bangladesh to have more than 200% cropping intensity in many regions. In fact, the *Boro* paddy crop accounts for over 90% of the total irrigation consumption in Bangladesh (Amarasinghe et al. 2014).

Development of the groundwater-irrigated area (GWIA), which has increased fourfold over four decades (1970-2010), has moderated the impacts of recurrent droughts in the basin. For example, lower than average rainfall was experienced during the periods 2001-2003 and 2009-2010, but there was only a slight decrease in NIA and GIA compared to the reduction in rainfall (Figure 4[d]). In fact, GWIA has increased in years with hydrological droughts (when surface runoff is lower than average).

Increasing Groundwater Irrigation

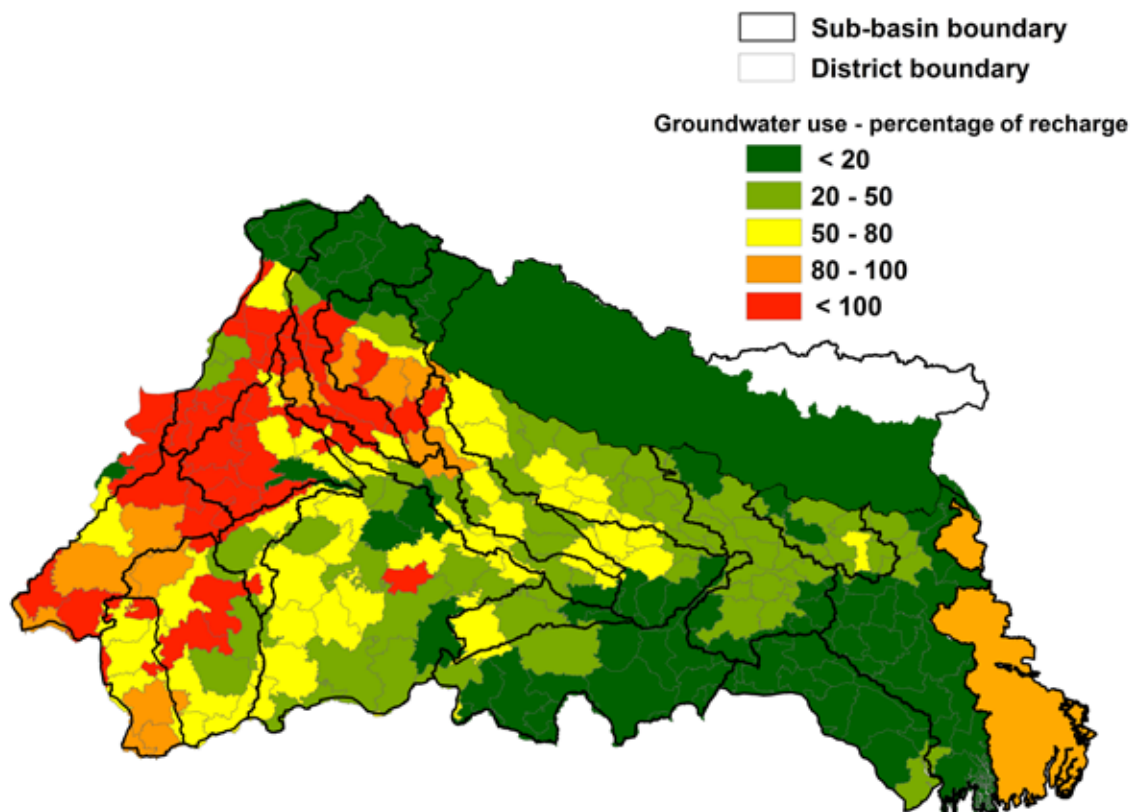
Increase in groundwater irrigation has brought both positive and negative impacts to the basin. Groundwater irrigation has contributed to nearly all of the irrigation expansion (Table 1). Between

1971 and 2011, GIA and GWIA increased by 25 Mha and 23 Mha, respectively, in the GRB, and much of the increase in GWIA (about 21 Mha) is in the Indian riparian region. Importantly, this has contributed to an increase in crop productivity and production in the basin. Food grain production increased by 75 million metric tons (Mmt), while the food grain area only increased by about 7 Mha between 1971 and 2011.

Irrigation, particularly groundwater irrigation in the GRB, was a vital factor for the increased crop productivity in the past few decades. While the land productivity of food grains more than doubled (from 0.84 to 2.09 tonnes/ha) between 1971 and 2011, the physical water productivity of food grains increased from 0.24 to 0.60 kg/m³. In 2011, GRB produced about USD 49 billion of crops (in export prices), which included USD 31 billion of food grains. This enhanced the livelihood security of millions of the riparian population, and contributed substantially to reducing rural poverty from 43% in the early 1990s to 24% by 2011.

However, groundwater expansion has also contributed to over-exploitation of the resource (Figure 5). Already, the middle and upper Yamuna sub-basins in the western region have exhausted their total groundwater resources. Groundwater depletion in several other sub-basins in the west and in the Bangladesh riparian region in the east exceeds 80% of the available groundwater resources. These sub-basins have large pockets of over-exploited groundwater resources. While any further increase in process CWU would only exacerbate the unsustainable water use in much of the western region, a vast potential exists for groundwater exploitation in the eastern part of the GRB.

FIGURE 5. Groundwater CWU as a percentage of groundwater recharge.



Water Storage Changes

Building surface water storage is the common response to buffering water resources variability. The surface storage potential in the GRB is as shown below:

- The Indian riparian region had increased its storage capacity to about 48.7 Bm³ by 2013. This, along with surface storage with a capacity of 7.6 Bm³ under construction, will exhaust much of the potential surface storage capacity (84 Bm³) in the Indian riparian region (Gol 1999). However, construction of the remaining part of the potential storage will be a difficult task due to socioeconomic and environmental concerns.
- Nepal has large surface storage potential that can generate hydropower and augment streamflows during low-flow periods. Yet, less than 1% of that

potential has been developed (GoN 2011).

- Bangladesh has limited potential for surface water storage due to its flat topography.

The hydro-economic analysis of surface storage in the GRB by Jeuland et al. (2013) highlighted that, even if much of the storage potential in Nepal is harnessed, it will have limited buffering impact on flood peaks downstream. Sadoff et al. (2013) suggested that improved groundwater management could benefit the GRB. Moreover, Khan et al. (2014) investigated the potential for flood reduction through conjunctive water use management strategies: pumping along canals, and distributed pumping and recharge, which are essentially the subsets/elements of the GWM focusing only on artificial recharge. Results of this study showed that 6% to 37% of the flood volume in Uttar Pradesh could be stored in the subsurface, thus leading to a reduction in flood damage.

TABLE 1. Area, production and consumptive water use of all crops and food grains.

Factors	Units	Indian riparian region						GRB			
		1971	1981	1991	2001	2011		1971	1981	1991	2011
Gross cropped area (GCA)	Mha	52.8	55.8	58.1	64.3	66.3		60.1	63.4	66.0	71.2
Gross irrigated area (GIA)	Mha	13.0	18.0	23.8	34.6	36.3		14.8	21.1	28.3	40.1
GIA as a percentage of GCA	%	25	32	41	54	55		23	31	40	55
Groundwater-irrigated area (GWIA)	Mha	6.4	9.9	14.4	24.7	27.4		6.6	10.3	15.2	28.9
GWIA as a percentage of GIA	%	49	55	60	71	76		49	53	57	71
Value of crop production	USD (billions)	4.6	17.8	23.9	24.1	44.1		5.3	20.2	27.0	48.9
Consumptive water use of all crops	Bm ³	194	205	214	237	239		220	233	242	265
Economic water productivity of all crops	USD/m ³	0.02	0.09	0.11	0.10	0.18		0.02	0.09	0.11	0.18
Food grain area	Mha	42.4	44.2	44.3	48.3	46.9		48.2	51.0	51.7	55.0
Food grain production	Mmt	33.7	46.3	67.1	90.0	95.8		40.3	54.7	78.6	115.1
Food grain yield	tonnes/ha	0.79	1.05	1.51	1.86	2.04		0.84	1.07	1.52	2.09
Irrigated food grain area	Mha	10.6	14.6	18.4	26.6	28.2		11	16	21	33
Irrigated food grain area as a percentage of the food grain area	%	25.0	32.9	41.4	55.1	60.2		23	31	40	60
Value of food grain production	USD (billions)	3.0	11.1	14.2	14.9	26.2		3.6	13.1	16.6	31.4
Consumptive water use of food grains	Bm ³	142	148	149	162	161		170	175	174	192
Physical water productivity of food grains	Kg/m ³	0.24	0.31	0.45	0.55	0.60		0.24	0.31	0.45	0.60
Economic water productivity of food grains	USD/m ³	0.02	0.07	0.10	0.09	0.16		0.02	0.07	0.10	0.16

Notes: Consumptive water use of the GRB is estimated based on the water productivity of the Indian riparian region.

As indicated in Sadoff et al. (2013) and Khan et al. (2014), and also by the recent trends, it is clear that groundwater irrigation can increase crop production and social benefits immensely. However, what is not clear is the potential of the GWM, because of the substantial hydrological and environmental changes over the last 40 years. The development of a sustainable GWM, at scale, should necessarily satisfy the following three conditions.

- There should be a sufficient demand for water for consumptive needs, and if met by an increase in groundwater pumping, it would create additional SSS.
- There should be adequate surface runoff (generated during the monsoon season) in excess of environmental flow requirements available for recharge.
- It should be feasible to recharge SSS through both natural and artificial means.

The Potential

Water Accounts of the Basin

The Indian and Nepal riparian regions generate 93% of the annual runoff in the GRB (Table 2). Much of the water supply in Nepal is from surface runoff, and a large part of that surface runoff flows across the border into India and contributes to runoff of the Indian riparian region of the GRB. As a result, the Indian riparian region contributes to 95% of the total renewable water resources (TRWR), of which the potentially utilizable water resources (PUWR) is only one half (Gol 1999). Groundwater contributes to 32% of TRWR and

97% of that is available in the Indian riparian region. Internally Renewable Water Resources (IRWR) of Bangladesh contribute to 5% of the TRWR.

Figure 6 shows water use for the four most recent years (2008-2011) for which the data are available to estimate CWU. The process CWU depleted 123 Bm³ (or about 22%) of TRWR. Irrigation is the largest contributor to process CWU (about 93%), for which groundwater made a substantial contribution (about 78%). Non-process ET consists of another 5% of TRWR. Thus, at present, total water depletion as process and non-process ET in the basin is only 27% of TRWR.

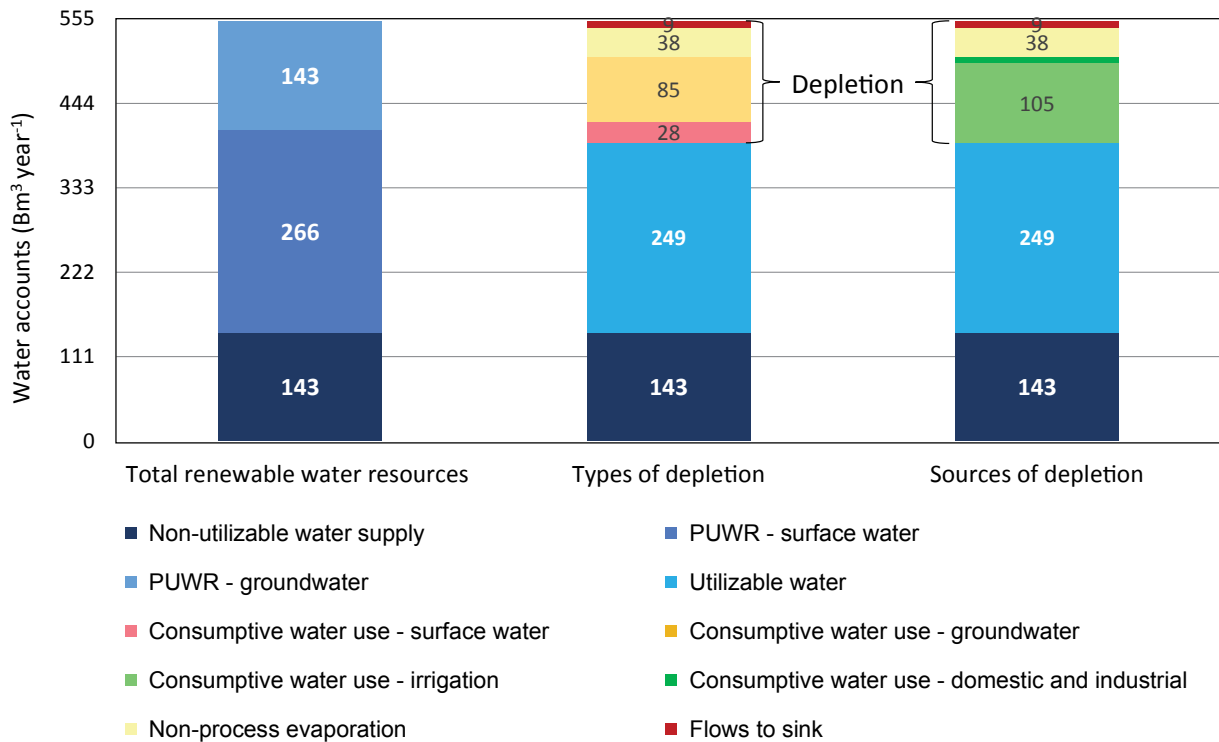
TABLE 2. Water supply in the GRB.

Country	Internally renewable water resources (Bm ³ /year)		Inflow from other countries (Bm ³ /year)	Total renewable water resources (Bm ³ /year)	Storage capacity (Bm ³)
	Surface water	Groundwater			
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	53.11

Sources: AQUASTAT database (FAO 2011); Gol 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.

FIGURE 6. Water use accounts of the GRB.



Sources: Figures for utilizable surface water, groundwater and non-utilizable water - Gol 1999. Other water accounting figures are the authors' estimates.

Importantly, the water accounts show that only 7% (i.e., 28/375) of the surface water resources are depleted (process CWU) at present. However, this depletion could be a slight underestimate, because a part of the groundwater CWU from the reuse of return flows of surface water withdrawals are not accounted for here, and part of the non-process ET is also from surface withdrawals. Nevertheless, it is clear that a large part of the surface runoff, most of which is generated during the monsoon season, is uncommitted (either not used or not committed as EFs, navigation, etc.) at present. For instance, mean annual flow of the Ganges River observed at the Hardinge Bridge in Bangladesh (just below the Indian border) was 347 Bm³ since 2000.

Water Accounts by Sub-basin

Table 3 provides the estimated surface runoff for the sub-basins (Muthuwatta et al. 2015), which also summarizes the details of water accounts for these 21 sub-basins. The water accounts in Table 3 include the following:

- Available water resources: mean surface runoff (Table 3, column C2), runoff that has 75% exceedance probability (i.e., flow that may be expected, on average, in three out of four years) (Table 3, column C4), and groundwater resources (Table 3, column C6).
- Process ET from surface water (Table 3, column C7) and groundwater (Table 3, column C8).

- Uncommitted surface water (Table 3, column C11) and groundwater (Table 3, column C12) resources.

Most sub-basins have sufficient surface runoff to meet an increase in process ET without tapping into EFs. The ratio of total ET (process and non-process) from surface water withdrawals to average surface runoff varies from as low as 7-9% in the Kosi, Ghaghara and Son sub-basins to more than 82% in the upper Yamuna sub-basin (Table 3, column C9). In fact, the ratio of ET from surface withdrawals to dependable surface runoff is below 15% in 11 sub-basins and below 25% in all sub-basins, except for the lower, middle and upper Yamuna, Lower Chambal, Ghaghara and Gomti confluence and Gomti confluence up to Muzaffarnagar sub-basins. Altogether, 17 sub-basins have sufficient runoff to meet additional ET.

However, many sub-basins have a substantially high level of groundwater use (Table 3, column C10). The ratio of groundwater ET to groundwater resources is nearly or over 100% in five sub-basins (upstream of Ramganga confluence, Banas, Ramganga, and middle and upper Yamuna). These sub-basins have widespread or large pockets of over-exploited groundwater resources, and the status of these sub-basins is as shown below:

- The middle and upper Yamuna sub-basins have high levels of groundwater and surface water depletion. Any further increase in ET in these sub-basins would

leave very little water for EFs, and will only aggravate unsustainable water use.

- The other three sub-basins: upstream of Ramganga confluence, Banas and Ramganga have high groundwater ET (Table 3, column C10), but low surface water ET (Table 3, column C9) with respect to the renewable water resources. These sub-basins can adopt aggressive managed aquifer recharge (MAR) programs to reduce over-exploitation of groundwater resources.

The other sub-basins have adequate uncommitted surface runoff to increase SSS by increasing process groundwater ET (Tables 3, columns C11 and C12). However, this still depends on the need for additional water to meet the unmet irrigation demand.

Potential Unmet Water Demand

In the GRB, the demand for irrigation is low during the *Kharif* season, but high during the *Rabi* and hot weather seasons. Rainfall meets much of the CWU demand in July, August and September (Figure 7), and 70% of the process CWU in the *Kharif* season (June-October). Therefore, the potential for increasing IRCWU in the *Kharif* season is low. Thus, the potential unmet irrigation water demand is estimated only for the *Rabi* and hot weather seasons.

TABLE 3. Water accounts and potential for increasing IRCWU in the sub-basins of the GRB.

Sub-basin	Surface runoff (Bm ³ /year)			Surface runoff generated during the monsoon season (% of total)	Groundwater resources (2008-2011) (Bm ³ /year)	Total ET (2008-2011) (Bm ³ /year) (% of SR _{p75})		Surface water ET (2008-2011)	Groundwater ET (2008-2011) as a percentage (%) of groundwater resources	Uncommitted water resources (2008-2011) (Bm ³ /year)			
	Mean	SD	SR _{p75}			C7	C8			C9	C10	C11	C12
C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12		
1 Upstream of Ramganga Confluence	10.0	5.0	5.5	81	5.2	0.8	5.6	14	107	4.7	-0.4		
2 Banas	9.9	7.1	3.5	94	2.6	0.4	3.0	10	116	3.2	-0.4		
3 Bhagirathi ¹	-	-	-	-	21.7	1.8	2.7	-	12	Na	19.0		
4 Lower Chambal	2.2	1.4	1.2	95	1.3	0.4	0.8	36	64	0.8	0.5		
5 Upper Chambal	8.7	3.0	6.6	90	4.0	0.7	3.1	10	78	5.9	0.9		
6 Damodar ¹	-	-	-	-	9.7	1.0	1.1	-	12	Na	8.6		
7 Gandak and others	16.0	6.6	11.8	86	13.0	1.4	3.4	12	26	10.4	9.6		
8 Ghaghara	35.6	17.6	23.3	84	20.5	1.8	10.5	8	51	21.6	10.0		
9 Ghaghara and Gomti Confluence	4.7	2.1	3.3	88	7.7	2.2	2.9	68	37	1.1	4.8		
10 Gomti	13.6	7.3	9.8	91	8.5	1.8	4.8	18	56	8.0	3.8		
11 Kali Sindh	15.5	6.6	10.5	81	5.9	1.9	4.0	18	67	8.6	1.9		
12 Kosi	9.4	4.0	6.8	73	6.3	0.5	1.8	7	28	6.3	4.5		
13 Ramganga	15.6	7.8	10.1	83	7.8	1.0	7.8	10	99	9.1	0.0		
14 Son	19.5	7.9	14.1	85	9.3	1.3	1.1	9	12	12.8	8.1		
15 Tons	6.8	2.5	5.2	89	1.6	0.5	0.7	10	43	4.7	0.9		
16 Gomti confluence up to Muzaffarnagar	9.4	4.8	5.7	88	9.7	2.2	6.8	38	71	3.5	2.8		
17 Lower Yamuna	22.4	10.8	15.2	94	16.9	4.9	7.6	32	45	10.3	9.3		
18 Middle Yamuna	4.8	3.7	2.1	79	5.4	1.3	6.3	60	116	0.9	-0.9		
19 Upper Yamuna	7.2	3.9	4.5	83	8.5	3.7	8.9	82	105	0.8	-0.4		
20 Nepal	63.2	11.6	54.4	89	20.0	2.6	0.9	5	5	51.8	19.1		
21 Bangladesh	22.0	-	-	-	5.5	1.2	4.7	5	87	20.7	0.7		

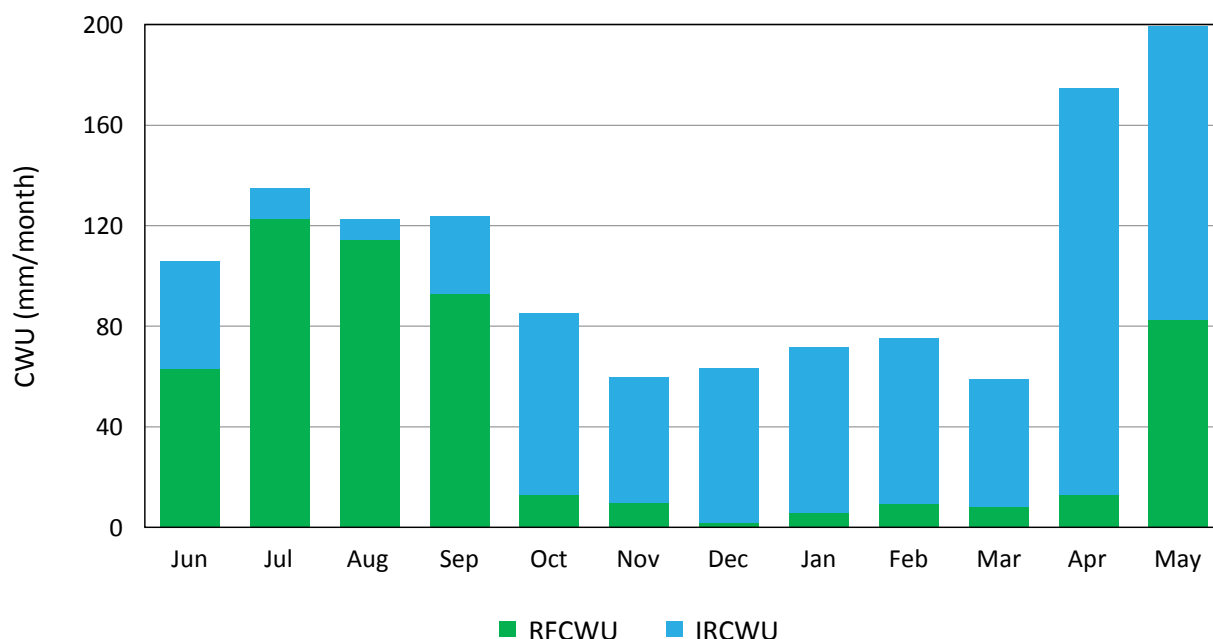
Sources: Runoff estimates (C2-C5) are from Muthuwatta et al. 2015; Groundwater resources are district-wise estimates from CGWB 2014; and ET estimates are from Amarasinghe et al. 2016.

Notes: ¹ Estimates of surface runoff are not available for the Bhagirathi and Damodar sub-basins.

C9 = C7 / C4, C10 = C8/C6, C11 = C4 - C7, C12 = C6 - C8

SD – Standard deviation; SR – Surface runoff; SW – Surface water; GW – Groundwater; Na - Not available.

FIGURE 7. IRCWU and RFCWU in irrigated crop areas in the GRB.



Rainfall only meets 30% of the total monthly CWU between November and March. Crop ET requirements are very high in April and May (Figure 7). Due to the gap between water supply and crop water requirements, the actual irrigated area, at present, is substantially lower than the potential.

In the Indian riparian region of the GRB, NSA is about 48 Mha at present, but the maximum cropped area is only about 37 Mha (Figure 4[a]). The cropped area in January, February, March and April is only 31, 25, 4 and 9 Mha, respectively. So, there is substantial scope to increase the cropped area in the *Rabi* and hot weather seasons. On the other hand, NIA in the Indian riparian region of the GRB is about 30 Mha, but the maximum irrigated area is about 26 Mha at present (Figure 4[b]), and the irrigated area in January, February, March and April is only 24, 21, 3 and 2 Mha, respectively. So, there is substantial scope to expand the irrigated area in the *Rabi* (November to March) and hot weather (April to June) seasons.

Two possible scenarios may be considered to expand the irrigated area in the Indian riparian region of the GRB during the *Rabi* (November-March) and hot weather (April-May) seasons.

- **Scenario A:** Provide irrigation to the total irrigable area, i.e., increase the irrigated area in the *Rabi* and hot weather seasons from 26 Mha and 3 Mha (current irrigated area during these seasons), respectively, to 30 Mha (irrigable area).
- **Scenario B:** Provide irrigation to the total cropped area. At present, not all cropped area is equipped for irrigation, i.e., irrigable area (or NIA) (30 Mha) is less than the total cropped area (37 Mha). Therefore, in this scenario, the aim is to increase NIA in order to increase the irrigated area from 26 Mha and 3 Mha in the *Rabi* and hot weather seasons, respectively, to 37 Mha.

Under scenario A, the potential increase in irrigated area in the *Rabi* and hot weather seasons is 4.13 Mha and 27.02 Mha, respectively. Under scenario B, the potential increase in irrigated area in the *Rabi* and hot weather seasons is 18.2 and 41.09 Mha, respectively (Table 4, columns C9-C12). However, given the current level of irrigation development, this potential varies from the western to eastern sub-basins.

Under scenario A:

- Many of the eastern sub-basins, such as Bhagirathi, Damodar, Gandak, Son and Kali Sindh, have substantial scope for bridging the gap between NIA and actual irrigated area in the *Rabi* season (Table 4, column C9). For example, 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 NIA, and is only 10% of the cropped area in the *Kharif* season. So, there is large potential for increasing the irrigated area in the *Rabi* season, and increasing the irrigable area to accommodate more cropped area.
- Potential for increasing the irrigated area between April and May is even higher. Although the scope for new irrigation in the *Rabi* season is high in the eastern sub-basins, almost all the sub-basins have the potential to increase the irrigated area in the hot weather season (Table 4, column C10). For example, in the Ramganga sub-basin in the upstream of the GRB, there is no potential to increase the irrigated area in the *Rabi* season, but there is potential to increase the irrigated area by 1.25 Mha in the hot weather season.

Under scenario B:

- The eastern sub-basins, such as Bhagirathi, Damodar, Son and Tons, have the potential to more than double the irrigable area (i.e., NIA). A substantial area in these basins has no irrigation facilities at present. For example, in the Bhagirathi sub-basin, NIA is 1.78 Mha, but the cropped area in the *Kharif* and *Rabi* seasons is 4.75 Mha and 2.12 Mha, respectively. Expanding the irrigable area would not only help meet the water deficits during critical periods of crop growth in the *Kharif* season, but will also help to increase the cropped area in the *Rabi* and hot weather seasons.

- The Gandak, Kali Sindh, Kosi and Lower Yamuna have the potential to increase NIA by more than 50%.
- Almost all the sub-basins have the potential to increase the irrigated area even in the *Rabi* season.

The Bangladesh riparian region in the downstream of the GRB has a similar situation to that of the Ramganga sub-basin in the Indian region. However, unlike the Ramganga sub-basin, there is no potential to increase the irrigated area between April and May (*Boro* season - equivalent to the hot weather season in the Indian region) in the Bangladesh riparian region, but there is potential to increase the irrigated area by 1.7 Mha between November and March (*Aman* season - equivalent to the *Rabi* season in the Indian region). However, the irrigation requirement is low in the *Aman* season. Therefore, the potential for increasing IRCWU is also low in this season.

The corresponding unmet irrigation demand for the potential increase in irrigated areas under scenarios A and B is 59 Bm³ and 125 Bm³, respectively (Table 5, C4-C5). However, realization of this potential is difficult given the current water use and availability in different sub-basins. In particular, in order to realize the potential increase in irrigated area, there should be either sufficient uncommitted groundwater resources or sufficient uncommitted surface runoff to recharge aquifers for subsequent withdrawals.

For example, in the one extreme are the middle and upper Yamuna, Banas and Upstream of the Ramganga confluence, which have already exhausted their groundwater resources (Table 5, C2), and a substantial part of TRWR (Table 5, C3). Any further increase in ET in these sub-basins would reduce the uncommitted surface runoff that is available at present for EFs, and would only exacerbate unsustainable water use. Therefore, there is no potential for increasing the irrigated area and hence groundwater CWU in these four sub-basins.

TABLE 4. Potential increase in irrigated area in the sub-basins of the GRB.

Sub-basin	Net irrigated area (NIA) (Mha)	Maximum monthly irrigated area (Mha)					Maximum monthly cropped area (Mha)					Potential increase in irrigated area ³ (Mha)				
		Jun-Oct	Nov-Mar	Apr-May	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	C12	Scenario B				
1 Upstream of 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 ¹	1.78	1.70	0.50	0.42	4.75	2.12	0.92	1.27	1.35	4.24	4.32					
4 Lower Chambal	0.41	0.22	0.39	0.00	0.40	0.53	0.00	0.02	0.41	0.14	0.53					
5 Upper Chambal	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 Ranganga	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 Gomti confluence up to Muzaffarnagar	1.95	1.15	1.95	0.23	1.55	2.17	0.24	0.00	1.72	0.21	1.93					
17 Lower Yamuna	3.86	1.71	3.64	0.05	4.53	6.19	0.05	0.22	3.82	2.55	6.15					
18 Middle Yamuna	2.14	1.04	2.14	0.06	1.44	2.46	0.06	0.00	2.08	0.32	2.40					
19 Upper Yamuna	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					

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 The periods for Bangladesh are May-August, August-November and November-April which coincide with the *Aus*, *Aman* and *Boro* seasons, respectively.

³ C9 = C2 - C4; C10 = C5; C11 = Max(C5,C6) - C3; C12 = Max(C5,C6) - C4.

On the other extreme are Bhagirathi, Damodar, Gandak, Ghaghara, Ghaghara and Gomti confluence, Gomti, Kosi and Nepal sub-basins. Not only do these sub-basins have very low groundwater use at present, but they also have sufficient groundwater resources to meet even the total irrigation requirements for the increased irrigated area. For example, the Bhagirathi sub-basin depletes only 12% of the groundwater resources at present, and the uncommitted groundwater resources are more than adequate to meet the irrigation requirement of 4.6 Bm³ and 15.1 Bm³ estimated under scenarios A and B, respectively (Table 5, columns C4-C5). These sub-basins have the most potential for increasing the irrigated area and groundwater CWU.

In between the two extremes are sub-basins, such as Son and Tons, with sufficient uncommitted groundwater resources to meet the irrigation requirement under scenario A but not under scenario B. They need substantial groundwater recharge to meet the irrigation requirement under scenario B.

Groundwater resources of a few other sub-basins, such as lower and upper Chambal, Kali Sindh, Gomti confluence up to Muzaffarnagar and Ramganga, are not sufficient to meet the irrigation requirement under both the scenarios. Only groundwater recharge through MAR would allow these sub-basins to meet the IRCWU requirements under scenario A.

Based on the above details, the sub-basins can be categorized into four groups (Figure 8) with different potential for the GWM, i.e., meeting unmet demand and creating SSS:

- Group 1 – High potential for the GWM
- Group 2 – Moderate potential for the GWM
- Group 3 – Low potential for the GWM
- Group 4 – No potential for the GWM

Group 1 - High potential for the GWM. This group of sub-basins has the highest potential for application of the GWM concept, and includes six sub-basins which are mainly in the eastern part of the GRB (Bhagirathi, Damodar, Gandak,

Ghaghara, Gomti and Kosi) and also the Nepal riparian region. The cycle of pump-recharge-pump is possible without any detrimental effect on EFs or sustainable groundwater use. The present levels of groundwater development in these sub-basins are low, and they have sufficient uncommitted groundwater resources to meet the increased IRCWU under scenarios A and B. In these sub-basins, natural interactions between groundwater and surface water can recharge SSS created by the depletion of groundwater resources. Based on the uncommitted surface water and groundwater resources, and present CWU, the Nepal riparian region is also included in Group 1.

Group 2 - Moderate potential for the GWM. This group of sub-basins has moderate potential for application of the GWM concept, and includes four sub-basins (lower Yamuna, Son, Ghaghara and Gomti confluence, and Tons) and the Bangladesh riparian region. The uncommitted groundwater resources of these sub-basins are sufficient to meet the increased IRCWU under scenario A, but not under scenario B. However, uncommitted surface water and groundwater resources in these sub-basins can meet the increased IRCWU under scenarios A and B. The potential for increasing groundwater CWU depends on the ability of MAR programs to capture the uncommitted monsoon surface runoff.

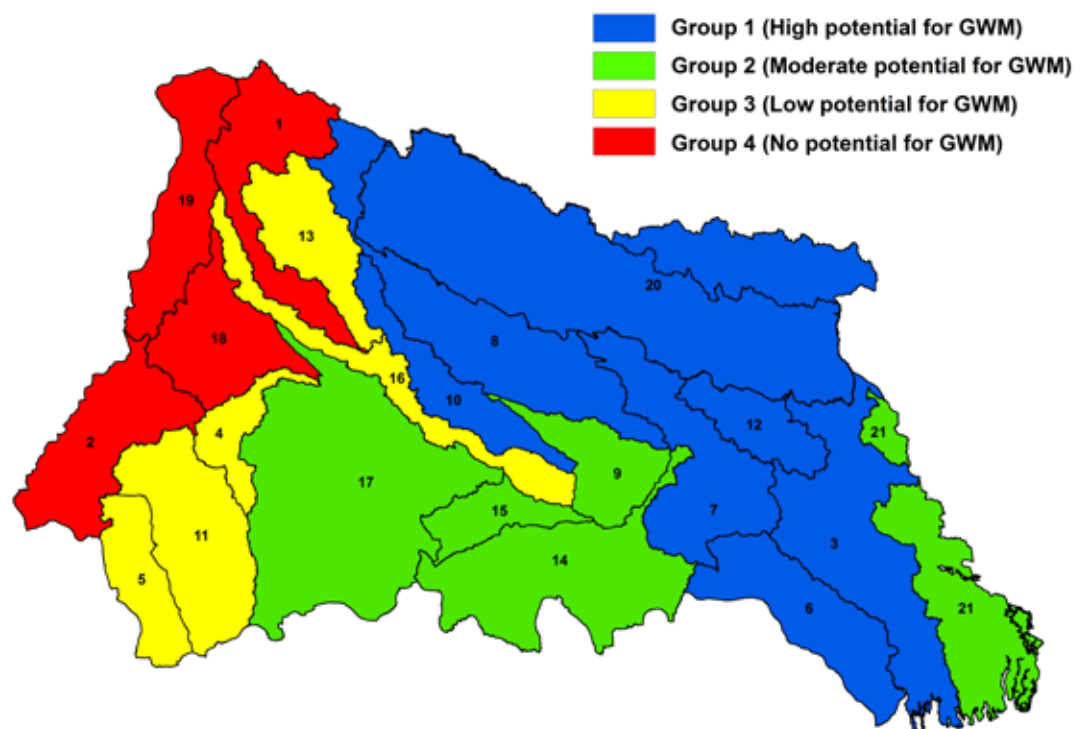
Group 3 - Low potential for GWM. This group of sub-basins has moderate potential for application of the GWM concept and includes five sub-basins: lower and upper Chambal, Kali Sindh, Gomti confluence to Muzaffarnagar, and Ramganga. The uncommitted groundwater resources of these sub-basins cannot meet the increased IRCWU under scenarios A and B. However, the uncommitted groundwater and surface water resources are sufficient to meet the increased IRCWU under scenario A. As in Group 2, these sub-basins also require MAR to capture the uncommitted monsoon surface runoff.

Group 4 - No potential for GWM. This group of sub-basins has no potential for application of the GWM concept, and includes four sub-basins: upstream of Ramganga confluence, Banas, and middle and upper Yamuna. The current levels of

water use in these sub-basins are very high, and the uncommitted water resources are insufficient to meet the increased IRCWU under scenarios A and B. If the increased IRCWU is achieved, it will be at the expense of the available water resources for other sectors (domestic, industrial and environmental flows), or it will aggravate the sustainable groundwater use.

It is noted that the surface runoff in the Bhagirathi and Damodar sub-basins was not available for this analysis. If surface runoff was also included in the total water resources, TCWU as a percentage of total water resources in these two basins would be much lower than that indicated in Table 5, column C3. Therefore, these two sub-basins are included in Group 1.

FIGURE 8. Estimated potential for application of the GWM concept in sub-basins of the GRB.



Note: Numbers (and names) of the sub-basins in the map correspond to those in column 1 in Tables 3, 4 and 5.

TABLE 5. Scenarios of a potential increase in IRCWU in the sub-basins of the GRB.

Sub-basin	Uncommitted water		Potential increase in IRCWU (November-May)				Realizable potential of unmet demand (November-May) (Bm ³ /year)				Potential for the GWM (grouping)	
	Groundwater - percentage of total groundwater resources (%)	Total - percentage of TRWR (%)	Total (Bm ³ /year)	Percentage of uncommitted groundwater resources ² (%)		Percentage of uncommitted total water resources (%) ²		Scenario A		Scenario B		
				Scenario A	Scenario B	Scenario A	Scenario B	Scenario A	Scenario B	Scenario A		Scenario B
C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	
1 Upstream of Ramganga Confluence	107	60	1.7	2.4	-452	-645	39	56	0	0	4	
2 Banas	116	56	1.2	4.1	-285	-961	44	150	0.0	0.0	4	
3 Bhagirathi ¹	12	21	4.6	15.1	24	80	24	80	4.6	15.1	1	
4 Lower Chambal	64	48	0.8	1.4	181	302	67	111	0.8	0.8	3	
5 Upper Chambal	78	36	2.6	5.1	296	592	38	76	2.6	2.6	3	
6 Damodar ¹	12	22	3.7	12.1	43	140	43	140	3.7	12.1	1	
7 Gandak and others	26	19	5.2	7.2	54	75	26	36	5.2	7.2	1	
8 Ghaghara	51	28	5.1	7.5	51	75	16	24	5.1	7.5	1	
9 Between Ghaghara and Gomti Confluence	37	46	3.4	2.9	70	60	57	49	2.9	3.4	2	
10 Gomti	56	36	2.6	2.8	70	75	22	24	2.6	2.8	1	
11 Kali Sindh	67	36	3.9	7.1	202	370	37	68	3.9	3.9	3	
12 Kosi	28	18	1.0	2.4	23	53	10	22	1.0	2.4	1	
13 Ramganga	99	49	2.5	3.3	5,189	6,901	27	36	2.5	2.5	3	
14 Son	12	10	1.9	11.3	24	139	9	54	1.9	11.3	2	
15 Tons	43	18	0.7	2.3	78	265	12	42	0.7	2.3	2	
16 Gomti confluence up to Muzaffarnagar	71	58	2.9	3.9	104	138	46	61	2.9	2.9	3	
17 Lower Yamuna	45	39	7.8	18.7	83	201	40	95	7.8	7.8	2	
18 Middle Yamuna	116	101	3.4	4.7	-395	-547	-33,156	-45,918	0.0	0.0	4	
19 Upper Yamuna	105	97	3.7	5.6	-874	-1,311	1,030	1,545	0	0	4	
21 Bangladesh	87	36	0.3	4.8	-452	-645	39	56	0.3	0.3	2	
Total			59.0	124.7					45.3		83.6	

Notes: ¹ The total water resources of the Bhagirathi and Damodar sub-basins in columns C6 to C7 only refer to groundwater resources.² Negative values in columns C6 to C9 indicate that all available water resources are already committed (hence negative uncommitted resources).

Costs and Benefits

The cost-benefit analysis (CBA) here considers a recharge plan only for meeting the unmet CWU demand of 45 Bm³ under scenario A in the sub-basins in groups 1 to 3. It further assumes that groundwater recharge will gradually increase to meet 4.5 Bm³ of CWU per year, thereby meeting the total unmet CWU demand in 10 years.

For estimating the cost, the CBA assumes the following:

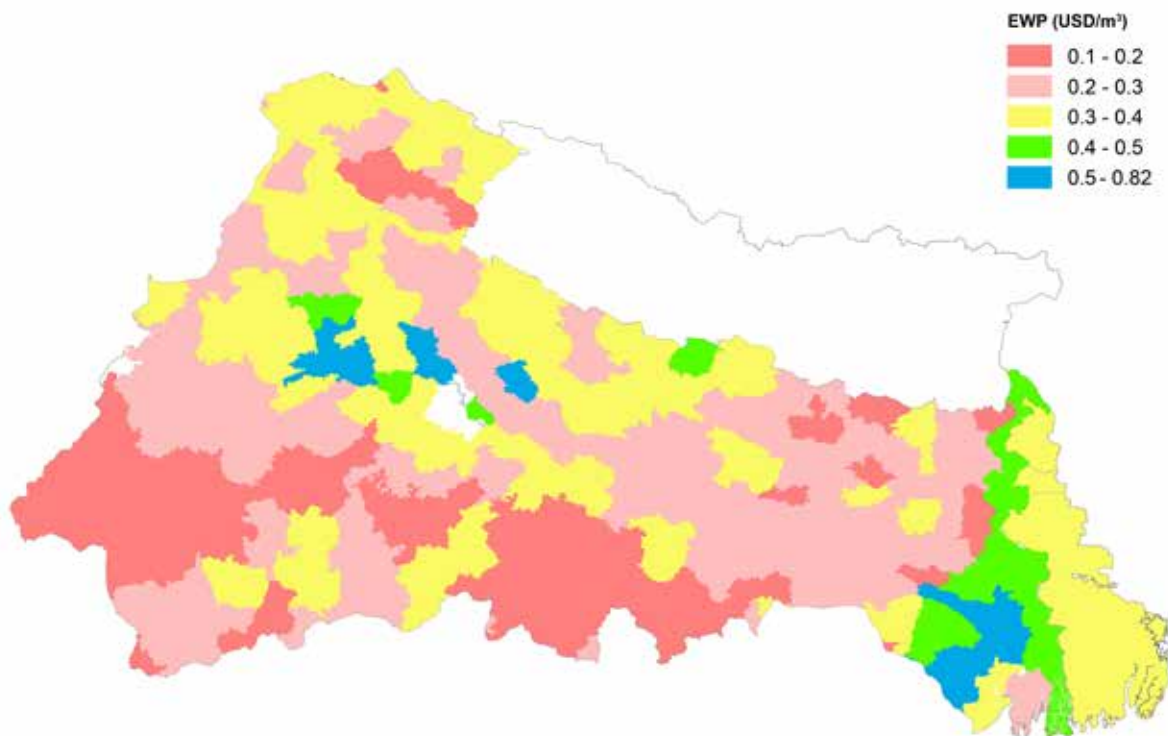
- The GWM requires about 75 Bm³ of additional groundwater withdrawals (at 60% irrigation application efficiency), and hence that amount of recharge for meeting the unmet CWU demand of 45 Bm³ in an irrigable area of 25.8 Mha.
- A recharge plan of 7.5 Bm³ per year over a 10-year period.
- The recharge plan will include recharge wells, where each well captures approximately 10,000 m³/year of floodwaters in SSS (i.e., 100 m³ of recharge per day in a maximum of 100 days of recharge during the monsoon season [Pavelic et al. 2015]).
- The current cost of a recharge well is about INR 75,000 or USD 1,150 (USD 1 = INR 65) (Prasun K. Gangopadhyay, field coordinator, IWMI, Delhi, pers. comm.). According to Sakthivadivel (2007), the capital cost estimate for a recharge injection well in an alluvial area was about USD 550 per well, with an operation and maintenance (O&M) cost of USD 20 per well. Therefore, the cost is assumed to range from USD 550 to USD 1,150 per recharge well.
- The O&M cost is 10% of the capital expenditure.
- Operational lifespan of a recharge well is 20 years.
- Annual discount rate is 8%.

The GWM requires about 750,000 recharge wells, which when spread over the total irrigable area is equivalent to 0.3 wells/ha. Thus, the capital cost for installing recharge wells is about USD 0.06-0.12/m³.

For estimating the benefits, the CBA assumes the following:

- The economic water productivity (EWP) of irrigation is USD 0.34/m³. The average EWP (ratio of value of production over TCWU) in the GRB in the period 2008-2011 is about USD 0.29/m³, and ranges between USD 0.10 and 0.82/m³ in the riparian districts of India (Figure 9). The EWP of major irrigated districts, where the irrigated area exceeds 75% of the cropped area, is USD 0.34/m³. We assume this as the crop water productivity of new irrigation.
- The cost of crop production is 75% of the gross value of output. The field sample survey of 600 farmers in the Ramganga sub-basin showed that the cost of production from diesel-powered groundwater irrigation is about 75% of the gross value of crop production. We assume this ratio as it reflects the cost of groundwater pumping in the region. Hence, the net EWP in the GRB is about USD 0.09/m³.
- A small portion (10%) of the recharged groundwater, in excess of the crop CWU demand, i.e., 75 - 45 = 30 Bm³, is assumed to meet domestic and industrial needs. It should, however, be noted that only 15-20% of this withdrawal is process depletion, and the remainder of the withdrawals are return flows to groundwater or surface water systems. The value of this water supply is also evaluated at the same rate as that of crop production.

FIGURE 9. Economic water productivity (EWP) of crop production in the GRB in the period 2008-2011.



Note: Data for Nepal were not available at the time this research study was conducted.

Recharge of groundwater is assumed to reduce flood damages by about one-third of the total damages in 2013, which is about USD 230 million/year. Although this value is used for demonstrational purposes, Pavelic et al. (2015) showed that a 50% reduction in flow could reduce the recurrence of severe floods from an interval of 16 to 2 years.

Table 6 shows the cost and benefits for a groundwater recharge plan of 7.5 Bm³/year over a 10-year period. The CBA illustrates the financial viability of the GWM under both capital cost scenarios, in spite of the potentially lower returns assumed for estimating agricultural, domestic and industrial water supply, and flood mitigation benefits. Further, this analysis has not captured the other social and ecosystem service benefits as a result of groundwater recharge, return flows, and more flows in low-flow periods in the rivers and tributaries.

The CBA has assumed that it requires to recharge 66% more floodwaters to meet all unmet irrigation demand, and the available groundwater irrigation infrastructure is adequate to pump water for irrigation. Additional recharge is possible in many sub-basins, such as Ramganga, where the groundwater table has been depleting rapidly in the past (Chinnasamy 2016). In such sub-basins, the GWM should first implement its groundwater recharge component. In other sub-basins, where there is no adequate SSS for recharge, the GWM should start with its pumping component. In the latter scenario, the natural interaction of surface water and groundwater could recharge much of SSS. This, in turn, would lower the capital, and operation and maintenance costs of recharge wells, although some capital cost is required for introducing additional pumps. Further assessments are required to identify where this is possible in the GRB and the implications on cost.

TABLE 6. Costs and benefits of the GWM.

Costs and benefits	Capital cost of recharge (USD/m ³)	
	0.06	0.12
Costs (USD billions)		
- Capital	2.99	6.25
- Operation and maintenance	2.54	5.31
Benefits (USD billions)		
- Irrigation	23.57	23.57
- Flood mitigation	1.55	1.55
- Domestic and industrial supplies	1.57	1.57
Benefit-cost ratio (BCR)	4.8	2.3
Internal rate of return (IRR)	0.9	0.4

Implementation Challenges

Locations for Managed Aquifer Recharge and Pumping

Although the above categorizing of sub-basins into four groups shows the broad picture of the potential for application of the GWM concept, there is substantial spatial variation of groundwater development and recharge within sub-basins at present. Even the sub-basins in Groups 2 and 3 can have locations where natural interactions are sufficient to recharge SSS created through groundwater depletion. Identification of these potential locations for pumping and recharge requires further disaggregated analysis and groundwater modeling.

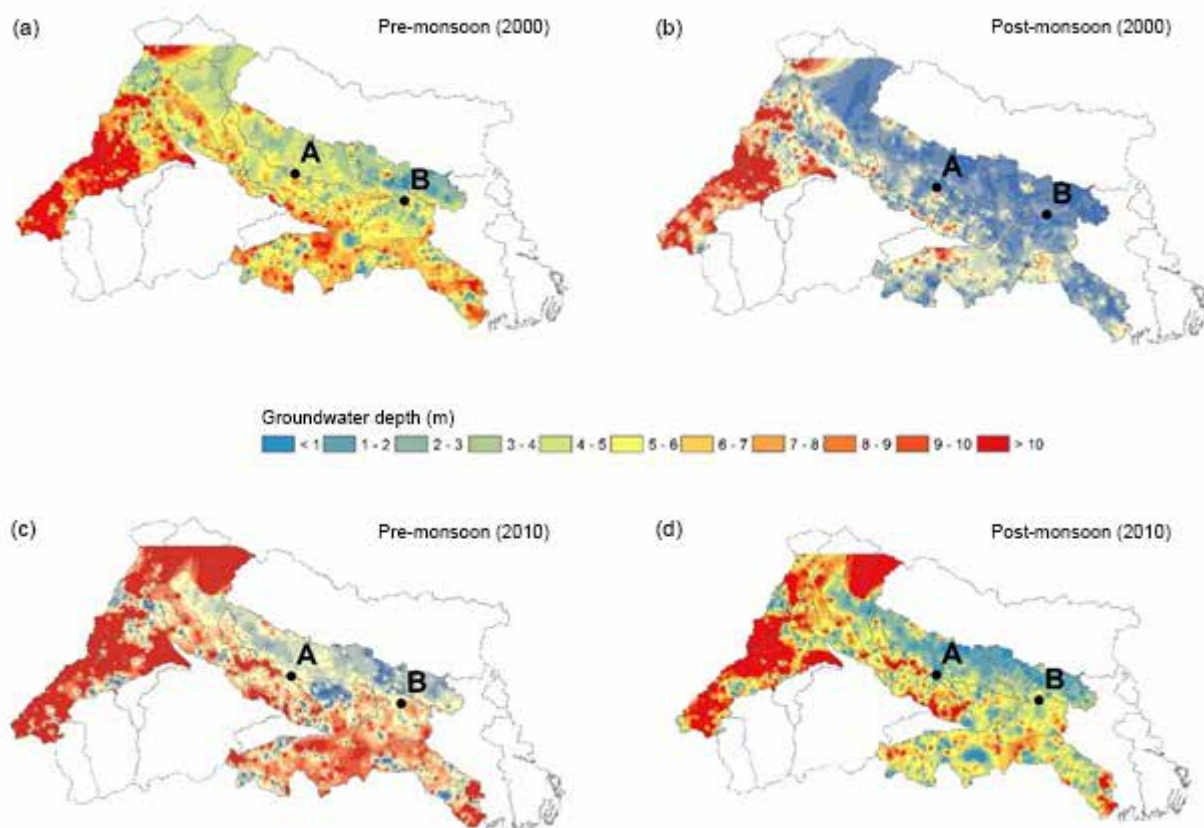
Groundwater depletion and recharge in the GRB are monitored through a large network of bore wells (CGWB 2014). Figure 10 shows the groundwater depth (below ground level) for a few sub-basins in the GRB, where reliable observations were available. It shows the pre-monsoon (end of May) and post-monsoon (end

of October) groundwater depths in 2000 and 2010.

Figures 10(a) and (b) show large fluctuations in groundwater depth as a result of depletion and recharge in 2000. Groundwater recharge from rainfall and other sources (e.g., surface irrigation), especially in the eastern and northeastern parts of the GRB, were sufficient to recover from the high levels of depletion before the monsoon. However, the situation has changed over time. By 2010, there were many pockets where the depth to groundwater was still high after the monsoon (Figures 10[c], 10[d]), indicating faster depletion than recharge.

For example, the depth to groundwater in many locations, such as at point A in Figure 10, has declined over time both before and after the monsoon (Figure 11, location A). In these locations, natural recharge during the monsoon is sufficient to compensate for the depletion before the monsoon. Further, groundwater use is not sustainable in these locations without MAR.

FIGURE 10. (a) and (c) Pre-monsoon, and (b) and (d) post-monsoon groundwater depths in a few sub-basins of the GRB in 2000 and 2010.



Note: Analysis of the depth to groundwater in the Indian riparian region is based only on the observations that are permissible to download from the Water Resources Information System of India (India-WRIS) open access database of the Central Water Commission (CWC), Ministry of Water Resources, Government of India, New Delhi, India (<http://www.india-wris.nrsc.gov.in/wris.html>). Data for the Nepal and Bangladesh riparian regions were not available for this analysis.

However, at location B, there was no significant decline in the depth to groundwater between 2000 and 2010 (Figure 11, location B). At location B, natural interactions between surface water and groundwater were sufficient to recharge the depleted aquifer. Locations similar to B have the potential for application of the GWM. In areas where there are declining trends in groundwater depth, MAR is necessary to ensure sustainable groundwater use, provided these areas have adequate uncommitted surface runoff.

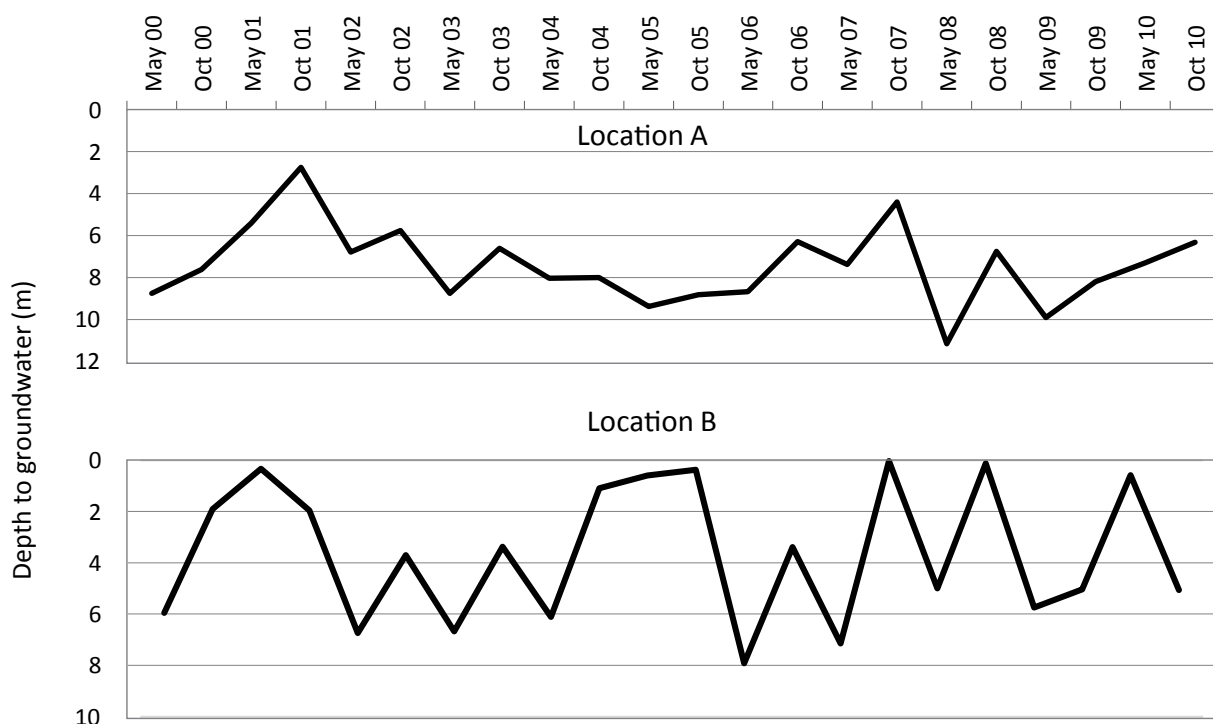
Energy for Pumping

The groundwater-energy nexus is the major barrier for implementation of the GWM. Electricity

consumption in the agriculture sector, which is primarily for groundwater pumping, has increased 22-fold over the last four decades in the Indian part of the GRB, and over 30-fold outside of the GRB (Figure 12). At present, electricity consumption per unit of groundwater CWU in the Indian part of the GRB is about 0.25 KWh/m³. At this rate of pumping, the demand for electricity for full-scale implementation of the GWM would require another 11,000-20,900 gigawatt hours (GWh). Access to this magnitude of additional electricity supply for agriculture would be a major issue given the current state of energy supply and demand in the riparian regions.

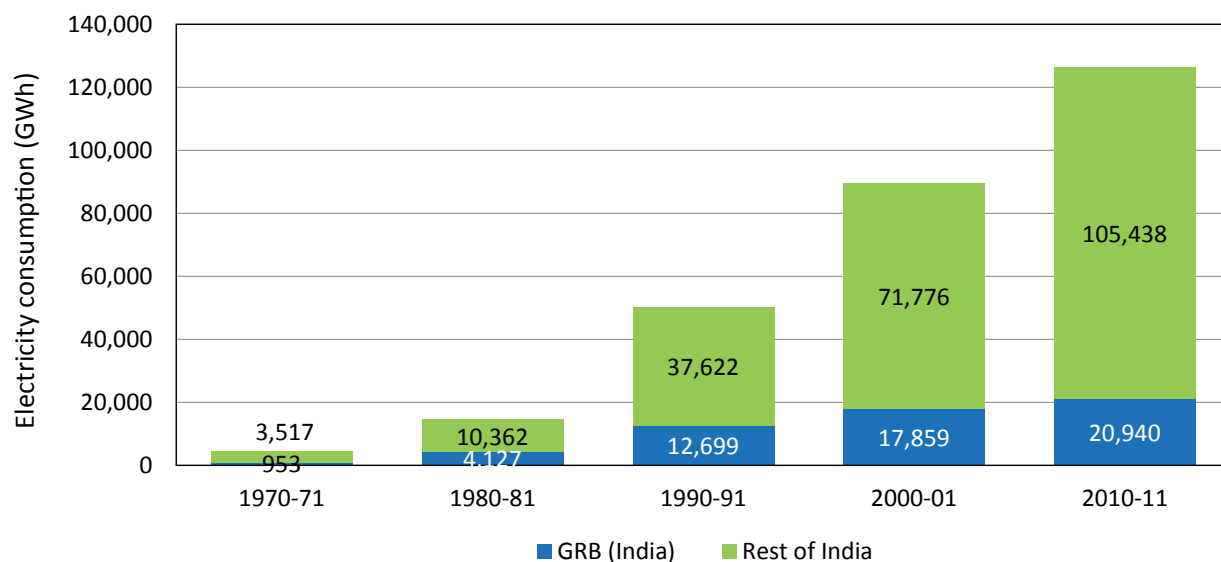
The agriculture sector accounts for 30% of the total electricity consumption in the Indian riparian region at present. In many areas, especially in the states of Uttar Pradesh and Bihar, electricity

FIGURE 11. Trends in the depth to groundwater before and after the monsoon at two locations in the GRB.



Note: The pre- and post-monsoon observations were carried out at the end of May and end of October, respectively.

FIGURE 12. Electricity consumption in agriculture in the Indian part of the GRB and outside the GRB.



Source: Authors' estimation based on state-wise data available at www.indiastat.com.

supply is available only for a few hours, and extended power cuts during the dry periods mainly in the summer months are a norm rather than an exception. Meeting the demand for electricity for groundwater pumping will be problematic, with the increasing demand in the domestic and industrial sectors (Amarasinghe et al. 2007). However, solar-powered water pumps may be the way forward for meeting energy requirements for pumping in the GWM.

Ex-ante analysis of the economic viability of solar-, diesel- and electricity-powered pumps in the Ramganga sub-basin in the GRB shows positive socioeconomic trade-offs of using solar pumps. Diesel-powered pumps were used by the majority of people in the surveyed area. The net income from groundwater-irrigated paddy cultivation using solar-powered pumps is INR 21,000 (USD 1 = INR 65), as against INR 26,000 and INR 15,000 using electricity- and diesel-powered pumps (Kakumanu et al. 2015). Given the high cost of diesel and unreliable supply of electricity, and also the high carbon emission and abatement cost, the solar-powered pumps are becoming a socioeconomically and environmentally viable investment.

The solar-powered irrigation pumps can be a solution to the emission challenges in the GRB. However, the high initial capital cost of these pumps is hindering adoption in the study districts, which have rich groundwater resources. Nevertheless, if the government considers the emission cleaning costs, it can use these funds to subsidize the price of solar-powered pumps.

The timeliness of irrigation without any shortages in the irrigation schedule also enhances water-use efficiency by 5-10% (Kishore et al. 2014). The tube wells that pumped 400-500 hours/year with diesel will pump 1,500-2,000 hours/year with solar (Shah et al. 2014). This can increase the recharge capability in the Ramganga sub-basin and

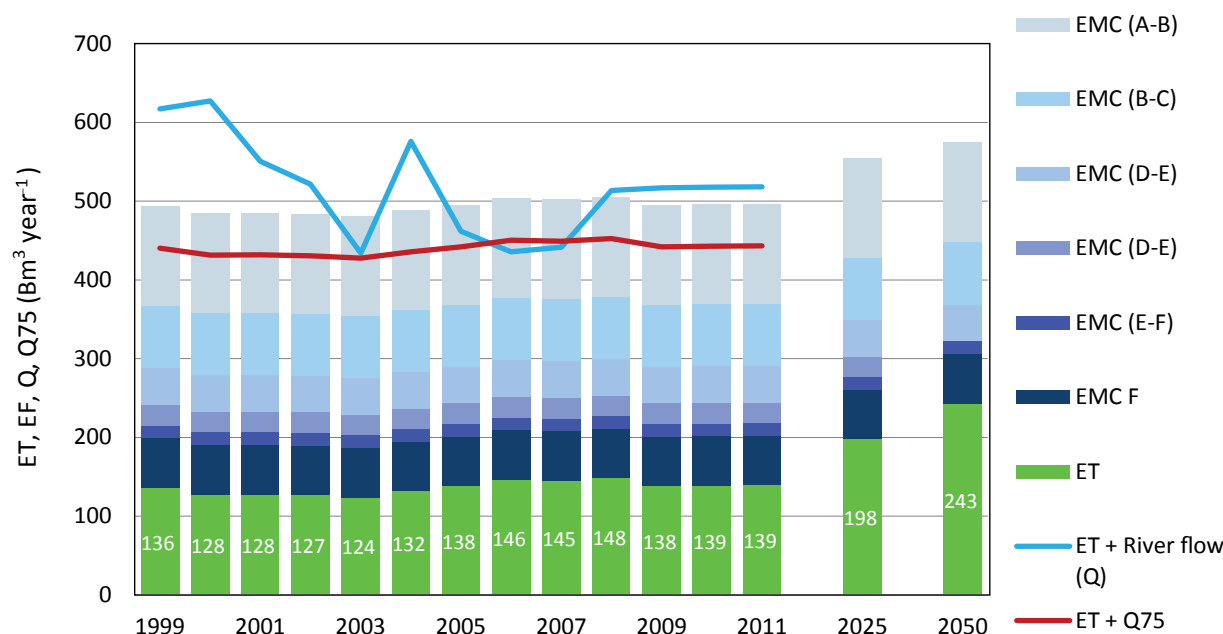
reduce the flood intensity to a little extent. Hence, in the groundwater-abundant areas of the northeastern states of India, the prevailing capital subsidy for the solar system would be useful to the marginal and small farmers, and bring socio-ecological benefits. In addition, promotion of solar with a buyback option, including an attractive feed-in-tariff, would help farmers to invest in the solar system (Shah et al. 2014)

Water for Environment

Environmental flows (EFs) – the water that is required to maintain rivers in the agreed environmental and social standards – may be seen as committed water flows in water accounting terminology. However, at present, there is no notified EF allocation policy in the GRB, although significant work in India, for example, is emerging (Smakhtin and Bharati 2016). Water demand projections of the Government of India allocated only 20 Bm³ of the mean annual runoff for EFs in 2050 (Gol 1999), which is even less than the total flow in the non-monsoon, low-flow period. However, more appropriate ways to estimate EFs for Indian rivers have been proposed recently.

Figure 13 shows estimates of EFs based on the method used by Smakhtin and Anputhas (2006) for managing the river under various environmental management classes (EMCs) - A (natural), B (slightly modified), C (moderately modified), D (largely modified), E (seriously modified) and F (critically modified). The lowest EF estimate for EMC F, shown by the bottommost blue cross-section (dark blue), is equal to 63 Bm³/year. The cumulative totals of the subsequent blue cross-sections show EF estimates for EMCs, i.e., EF estimate for EMC E is 79 (= 63 + 16) Bm³/year; EMC D is 105 (= 79 + 26) Bm³/year; EMC C is 152 (= 105 + 47) Bm³/year; EMC B is 231 (= 152 + 79) Bm³/year; and EMC A is 357 (= 231 + 126) Bm³/year.

FIGURE 13. ET and EF estimates for different environmental management classes (EMCs).



Source: ET estimates for 2025 and 2050 are from Amarasinghe et al. 2007.

Note: EMC F has the lowest EF requirement. EMC (E-F) shows the difference in EFs under EMCs E and F; EMC (D-E) shows the difference in EFs under EMCs D and E, etc.

The two line graphs in Figure 13 show the sum of CWU and the actual annual river flows (solid blue line), and the sum of CWU and Q75 river flows (solid red 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. This situation can only exacerbate in the future with increasing water demand and deterioration of water quality. By 2050, total ET (process CWU and non-process ET) is projected to be over 235 Bm³/year. In such an eventuality, the river flow will often be less than the EFs required for EMC B. Thus, EMCs A and B are realistically not possible to maintain with the future water demand, while EMCs E and F are generally considered unacceptable.

Figure 13 only illustrates annual values. EFs are even more critical for maintaining the health of the river during low-flow periods, and it is during these periods when the river flows

are already inadequate to meet this EF demand with increasing ET. The average river flow during the low-flow period over the last four decades (1971-2009) is only two-thirds of that during the previous three decades (1940-1970) (Figure 3[a]). The river flow in the low-flow period is likely to decrease further with increasing ET. Yet, the present average runoff of more than 340 Bm³/year is adequate to meet the EF of EMC C of 152 Bm³/year, and the additional process CWU water demand of about 85 Bm³/year projected for 2050.

Therefore, even if significant EF requirements are satisfied, the GRB (at the outlet from India to Bangladesh) still has around 200 Bm³ (i.e., 375-26-152) of surface runoff that can be depleted (withdrawn from the river) for other productive activities. However, the magnitude of surface flow, and the mechanisms to capture it through the GWM and beneficially use it vary across the sub-basins within the GRB.

Water Quality

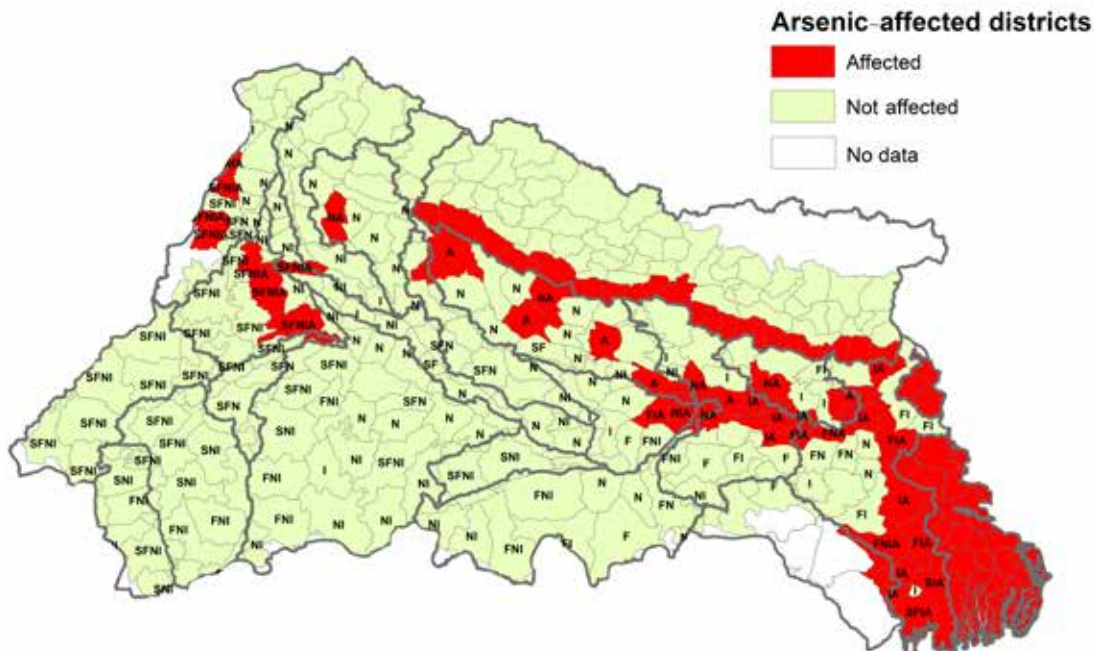
Groundwater quality is the key determinant of the ultimate potential of the GWM. Increased pumping-recharge-pumping cycle associated with the GWM has the potential to increase or decrease groundwater contamination.

On the one hand, increased return flows from the irrigation, domestic and industrial sectors could contribute to contaminating the shallow groundwater aquifers with nitrates, ammonium, phosphates, heavy metals, bacteria and salinity (Chakraborti et al. 2011; Rajmohan and Prathapar 2014). Decreasing groundwater levels due to excessive pumping in the non-monsoon period could increase the inward flow from nearby surface water bodies. This, in turn, has the potential to increase groundwater contamination with arsenic, fluoride, iron, selenium, radon, etc. (Medema and Stuyfzand 2002).

Groundwater in many parts of the GRB already has high concentrations of arsenic, fluoride, nitrate, chloride and salinity (Saha et al. 2008; CGWB 2010; Rajmohan and Prathapar 2014). In particular, arsenic contamination is widespread, and is a major issue in several riparian regions in Bihar, Haryana, Uttar Pradesh, West Bengal, Nepal Terai and Bangladesh (Figure 14).

Figure 14 shows the districts with high concentrations of iron (I), fluoride (F), nitrate (N) and salinity (S). Iron contamination is high in the south and southwest regions. Pockets of high fluoride and nitrate contamination are reported in Bihar, Chhattisgarh, Delhi, Haryana, Jharkhand, Madhya Pradesh, Rajasthan, Uttar Pradesh and West Bengal. Moreover, Chakraborti et al. (2011) have reported high concentrations of boron, uranium, manganese, lead, nickel and chromium in West Bengal and Bangladesh.

FIGURE 14. Groundwater quality issues in the GRB.



Sources: Saha et al. 2008; CGWB 2010; Rajmohan and Prathapar 2014.

Note: 'S', 'F', 'N', 'I' and 'A' on the map indicate the presence of salinity, fluoride, nitrate, iron and arsenic, respectively, in groundwater.

Data for Nepal and Bangladesh only include the arsenic-affected areas.

On the other hand, increased recharge could remove or dilute some contaminants in the groundwater. Many studies have reported that groundwater recharge from the monsoon rainfall has either diluted or flushed out nitrates, irons, clay materials and microorganisms, including bacteria (*E. coli*, clostridium spores and bacteriophage) (Parimalarenganayaki and Elango 2014).

Figure 14 also shows the districts affected by water quality issues. This, however, does

not mean that contaminants in groundwater are widespread throughout the districts. The challenge for operationalizing the GWM lies with identifying the locations, and the extent of pumping and recharge to reduce the contaminants in the groundwater. This requires including water quality parameters in detailed surface water and groundwater modelling for assessing the location-specific potential for application of the GWM.

Conclusions

Groundwater is the main source of supply for water development and process depletion (CWU) in the GRB. The reliance on groundwater will further increase due to increasing demand for water during non-monsoon seasons, and limited potential to further develop surface storages. Although it is now 40 years since the notion of the GWM was first put forward, there has hardly been a structured progress in its implementation. There are parts of the GRB where groundwater has been developed significantly, resulting in a steady decline in groundwater level, which could have been arrested if recharge had been enhanced beyond natural rates. On this backdrop, application of the GWM may be the way forward for meeting additional water needs, and mitigating the impacts of floods and droughts in the GRB.

Lack of knowledge on some of its key drivers precludes implementation of the GWM in the GRB. From a purely biophysical point of view, spatial variation in unmet demand for irrigation, excess runoff generated during the monsoon season, and the capacity of the aquifers to store water are not adequately known. However, the preliminary and macro-scale analysis of this report shows that there is substantial unmet demand

for increasing the irrigated area and process depletion. Yet, water development to date has been so intense in four sub-basins – Upstream of Ramganga confluence, lower Chambal, and middle and upper Yamuna – that not much water is available for further exploitation. If additional development depletes more water, it will be at the expense of CWU in some other sectors or the environment.

The analysis also shows that application of the GWM concept is partially possible in some sub-basins (lower and upper Chambal, Kali Sindh, between Ghaghara and Gomti confluence, Ghaghara, Gomti confluence up to Muzaffanagar, Tons and lower Yamuna), and fully in others (Bhagirathi, Damodar, Gandak, Ghaghara, Gomti, Kosi, Son and Nepal). Due to the patterns of irrigation requirement, additional irrigation in the *Rabi* and hot weather seasons has the highest potential for depleting groundwater resources and creating SSS. The potential unmet demand under the two scenarios considered in this report range from 59 to 119 Bm³. However, due to supply constraints in some sub-basins, the available water resources can only meet about 45 to 84 Bm³. Potential in the sub-basins can be characterized as shown below:

- The Bhagirathi, Damodar, Gandak, Ghaghara and Kosi sub-basins can only use its naturally recharged groundwater resources to meet the unmet irrigation demand for fully utilizing the current net irrigated area.
- Application of the GWM with natural recharge and MAR can provide irrigation water to utilize the entire net irrigated area in all the sub-basins, except for lower Chambal, Ghaghara and Gomti confluence, and upper and middle Yamuna.
- Application of the GWM can provide irrigation to utilize the entire net sown area in the Gandak, Ghaghara, Ghaghara and Gomti confluence, Gomti, Kosi, Ramganga and Tons sub-basins.

The preliminary analysis of benefits and costs shows that application of the GWM could be a financially viable solution for water-related issues in the GRB. However, the ability to realize its potential depends on many other conditions, which include the following:

- Most importantly, access to energy for additional pumping, and access to land for MAR interventions. Preliminary observations of this paper show that solar-powered pumps could be a solution to energy scarcity and for implementing the GWM in the GRB.
- Surface water quality is a serious issue in many regions. Where and how to recharge surface water sources requires location-specific analyses.
- Properties of the soil and 'crop holidays' (a period of time when the cultivation of a particular crop does not take place) are required for the soil in between intensive cropping in the *Rabi* and *Kharif* seasons.

- People's willingness to increase cropping and irrigation intensities from about 135%, at present, to 200-300% with more groundwater irrigation. Questions on why people do not increase cropping intensity even in locations with adequate groundwater resources, and whether any socioeconomic and institutional factors are constraining them from doing so, need to be examined.
- Population pressure in the GRB is already high and will only further increase in the future. Therefore, any displacement of people or submergence of land due to MAR or, for that matter, any other infrastructure development would be major issues of contention for implementation of the GWM, because many of the people who would be affected by such development activities are the smallholders and marginalized population.
- Due to limited data availability and lack of sharing the available data, the modelling of surface water and groundwater interactions for a large river basin such as the Ganges is difficult. Whether application of the GWM concept can realize SSS potential requires further in-depth hydrogeological studies.

Regardless of the constraints above, the benefits of developing only a small portion of such potential storage are likely to be enormous. Besides irrigation benefits, it can buffer rainfall variability and reduce extreme flooding, especially in downstream regions. SSS can increase river flow during the low-flow period either through baseflow or reallocation of canal irrigation. Importantly, it can mitigate the negative effects of floods and water scarcity in the same year. While this may not be a panacea for water availability and scarcity issues throughout the GRB, the GWM approach can surely help alleviate these issues in parts of the Ganges, and needs to receive more attention now than it did in the past.

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