

Chapter 35

Improving Water Security to Mediate Impacts of Climate Change in the Ganges Basin



B. Sharma, P. Pavelic, and U. Amarasinghe

Abstract In spite of being water surplus, the 600+ million population of the large Ganges basin spread over 1.09 m km² in South Asia is water insecure, poor, and highly exposed to water-induced stresses of floods and droughts. The contribution from the glaciers to the streamflow is ~70% in the Himalayan catchments though spatially distributed quantification is unavailable. An application of the *Water Evaluation and Planning (WEAP) model* with a sub-routine for snow and glaciers melt processes in the basin was set up. The model also examined the possible impacts of an increase in temperature of +1, +2 or +3°C over 20 yrs of the simulation period. The impact on stream flows was high in the upstream (+8 to +26% at Tehri Dam) and moderate in downstream (+1 to +4% at Farakka). These increases shall create flood events more frequently or of higher magnitude in the mountains and Upper Ganga flood plains. To moderate the climate-change induced impacts of floods and improve water security during the non-monsoon season the novel concepts of Underground Taming of Floods for Irrigation (UTFI) and Cranking up the Ganges Water Machine for Ecosystem Services (GAMES) were developed, and pilot tested in the Ramganga sub-basin. Analysis showed that there is an assured possibility of reducing the floods and enhancing sub-surface storage in the identified basins to the level of 45 Bm³. The demonstrated managed aquifer recharge interventions are technically feasible, operationally acceptable and economically viable.

Keywords The Ganges basin · Climate change · Water evaluation and planning model · Underground taming of floods for irrigation · Ganges water machine for ecosystem services

B. Sharma (✉)

International Water Management Institute, India Office, NASC Complex, New Delhi, India
e-mail: b.sharma@cgiar.org

P. Pavelic

International Water Management Institute, South-East Asia Office, Vientiane, Laos

U. Amarasinghe

International Water Management Institute, Colombo, Sri Lanka

35.1 Introduction

The Ganges basin is one of the largest and most populous river basins in Asia with a population of more than 655 million. It is distributed between India (79%), Nepal (13%), Bangladesh (4%), and China (4%). It covers a total area of 1,086,000 km² (Jain et al. 2007). The total length of the river Ganga from the source at Gangotri to its entry into the Bay of Bengal is 2,525 km. The Ganga River drains a basin of extraordinary variation in altitude, climate, land use and cropping patterns. Basin elevations range from 8848 m to sea level. Topographic contrasts in the basin are the largest compared to any other basin on earth and can be appreciated by the fact that within a distance of nearly 200 km, the elevation plunges from the highest mountain in the world at 8848 m (Mt. Everest peak in Nepal) to about 100 m (the elevation of the flat Ganga plains in India) (Fig. 35.1, Jain et al. 2016). The water availability in the Ganges basin is high, as on an average hydrological year around 1200 billion m³ (BCM) of precipitation falls in the basin. Of this, around 600 BCM becomes streamflow with the rest directly recharging groundwater or returned to the atmosphere through evapotranspiration (World Bank, 2013). There is however a tremendous variability in the spatial and temporal distribution of water supplies. The South Asian monsoon largely defines the climate and hydrology of the Ganga system. Snow and ice melt together have been estimated to contribute about 9% (almost 2/3 from snow) of total annual flows in the Ganga (Immerzeel et al. 2010), though they contribute much more in some

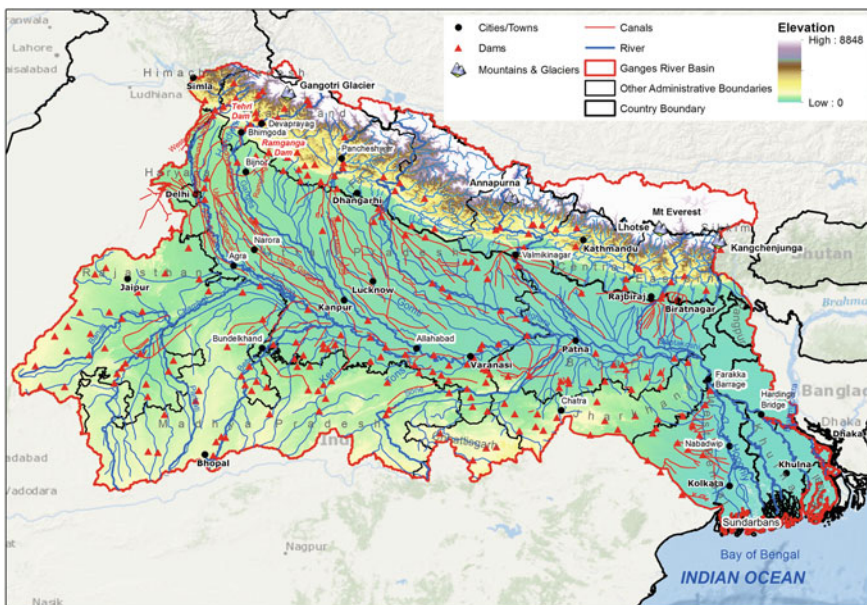


Fig. 35.1 Ganges Basin map showing existing dams, barrages and major canals (Source <https://gisserver.civil.iitd.ac.in/grbmp/downloaddataset.aspx>)

tributaries (e.g., 30% of annual flow in the Buri Gandak basin), and in small upstream catchments. Snow and ice comprise 2.4, 0.5 and 0.04% of the Ganges source (2004 km²), Ghaghara (570 km²) and Upper Yamuna (11 km²) catchments, respectively. The Ganges basin has a total of 1,020 large glaciers. Mean annual precipitation varies significantly throughout the Basin: rainfall is highest in the eastern Himalayan belt and in the delta areas (>2000 mm), and lowest in the desert of Rajasthan in the west (<250 mm).

The predicted rise in temperature across the basin will alter the timing and magnitude of contributions from snow and glacier melt to the Ganges. In the medium term, melting in the Himalayas will begin earlier in the year and persist longer and thus increase the runoff (Rikiishi and Nakasato 2006). In the long term, the consistent contributions from meltwater will decrease as storage gradually declines (Alford and Armstrong 2010). Seasonal storage in the form of snow will decrease, and more variable rainfall and the resultant floods will then become increasingly dominant (Miller et al. 2012). There is an urgent need to understand these potential impacts of climate change on variability of the water resources in the basin and devise suitable strategies and interventions to mediate these impacts. By employing specific routines of the Water Evaluation and Planning (WEAP) model, this study simulates the impact of rise in temperature of 1, 2 and 3°C over a period of 20 yrs on the snow and glacier melt and stream flow in different parts of the basin. It then presents some novel innovations like Underground Taming of Floods for Irrigation (UTFI) and Cranking up the Ganges Water Machine for Ecosystem Services (GAMES) for making productive uses of the additional flood water available in the basin to improve the water security and the livelihoods.

35.2 Study Design

Water Evaluation and Planning (WEAP; <https://www.weap21.org/>) model, which contains an experimental glacier module that accounts for snow and glacier processes in the Ganges basin, i.e. seasonal mass variations and contributions to streamflow was used to have an estimate of the impact of temperature rise on snow and glacier melt. WEAP employs a unique approach where a database maintains water demand and supply information to drive a mass balance model on a link-node architecture. As climate change becomes an increasingly important challenge facing water managers, WEAP has expanded to include integrated hydrologic simulation functionality. With this enhanced version, dynamically integrated rainfall/runoff routines translate information on climate and catchment conditions into hydrologic fluxes that drive the existing water system simulation routines (Yates et al. 2005). The WEAP model helped to: (i) simulate the surface water resources in the Ganges basin with special focus on the contribution from snow and glacier melting, as well as the anthropogenic utilisation of the resources; and (ii) enable an effortless development of prospective scenarios to climate change (increase in temperature). The Ganges

basin was discretised with respect to elevation to account for the variation with altitude of the glacier coverage and climate. In the second step, WEAP was calibrated and partly validated on observed streamflows. In a third step, WEAP analysed the current context of the surface water resources in the Ganges basin, in particular the contribution from the melting of glaciers. We also examined possible impacts of an increase in temperature of +1, +2, or +3°C over 20 years. We proceeded by river system (e.g., Ganges, Yamuna, Koshi), from upstream to downstream, with a monthly calculation time step. Whenever large time series of observed data were available, i.e., more than 10 recent years, part of this time series was kept aside for validation. We also evaluated the quality of the WEAP-Ganges and found that it was satisfactory (as it was possible to simulate average monthly and annual flow trends) for the Nepalese sub-basins, where observed time series were available and where most of the glaciers are present. As such, it was possible to consider monthly average trends for glacier-related analyses. In several other sub-basins, the quality was variable and as such was good for providing average trends. Other limitations of the current version of WEAP-Ganges include the following and as such the results may be considered preliminary (Sharma et al. 2013):

- i. WEAP-Ganges does not cover the entire Ganges basin but just the part up to the Farakka barrage in India. Below that point the impact of glaciers on streamflows was rather small;
- ii. no time series for glacier coverage was available; hence the calibration of the WEAP glacier module aimed at reproducing streamflows, while an additional calibration target could be the variation of the glaciers' area;
- iii. the description of glacier behavior is based on a simple conceptual model, which may not capture all glacier processes.

As floods and droughts, along with over-exploitation of groundwater, were the major concerns in the Ganges basin, an approach referred to as the “Underground Taming of Floods for Irrigation (UTFI)” was developed and tested in the Ramganga sub-basin. This approach involves interventions at the river basin scale to strategically recharge aquifers upstream during periods of high flow, thereby preventing local and downstream flooding and simultaneously providing additional groundwater for irrigation during the dry season (Pavelic et al. 2015). The intervention mediates the flood impacts felt across one part of the basin to create groundwater recharge opportunities in another part of the basin.

A fresh look and analysis of the concept the Ganges Water Machine (GWM), a concept proposed 40 yrs ago, to meet the growing water demand through groundwater and to mitigate the climate- change induced impacts of floods and droughts in the basin was carried. The GWM provides additional sub-surface storage through accelerated use of groundwater prior to the onset of the monsoon season, and subsequent recharging of this sub-surface storage through monsoon surface runoff (Amarasinghe et al. 2016).

35.3 Results and Conclusions

The contribution from snowmelt and glaciers is important (60 to 75%) in Upper Ganga and in the Nepalese sub-division of Ghagra, Gandak and Koshi rivers (40 to 55%). The contribution however reduces significantly further downstream as flows from glaciated areas are diluted by stream flows generated by rainfall/ runoff processes. The average seasonal contribution is much contrasted, the flows from glaciated areas occur predominantly in the months of June to September, being almost nil in other months. Another interesting result is that glaciers are apparently buffers against inter-annual variability of rainfall. As evident from data under Table 35.1, annual streamflow contributions from glaciers have a smaller inter-annual coefficient of variation than annual flows generated by rainfall/ runoff and thus mediate the inter-annual variability of total annual streamflow.

This buffer characteristic is visible in sub-basins where the model setting is 'very good to good' during years with low rainfall (Table 35.2). In these cases, the proportion of streamflows which is generated from melting of snow and ice in glaciated areas is greater in dry years than during wet years, hence contribution from glaciated areas is important during years of weak monsoon.

Table 35.1 Partitioning of average annual streamflow generated from rainfall/runoff and glacier processes at Haridwar and Farakka (simulated for period 1982 to 2002)

Parameter	Haridwar sub-basin (upstream)			Farakka sub-basin (downstream)		
	Total	Rainfall/ runoff	Glaciers	Total	Rainfall/ runoff	Glaciers
Average flow, km ³ /yr	30.4	12.0	18.4	335.2	275.0	60.2
Coeff. of variation, %	11	20	11	21	24	8

Table 35.2 Average contribution from melting of snow and ice in glaciated areas simulated for some sub-basins where WEAP-Ganga's setting is 'very good to good'

N°	Sub-basin	Average proportion of annual stream flows from glaciated areas		
		For years 1982 to 2002	For 3 wet years	For 3 dry years
44	Busti	44%	40%	46%
46	Rabuwa Bazar	45%	40%	50%
51	Chatara Kothu	24%	22%	26%

35.4 Impact of Temperature Rise on the Melting of Glaciers

IPCC report (2007 and later) indicate that in Tibetan range, the temperature rise at the end of the century could be +3.8 °C. Studies by ICIMOD (2009) and other agencies provide information of the same magnitude. The study considered the following three scenarios:

- i. an increase of 1 °C after 20-yrs, i.e., a rate of +0.05 °C/year (optimistic),
- ii. an increase of 2 °C after 20-yrs, i.e., a rate of +0.10 °C/yr (business-as-usual),
- iii. an increase of 3 °C after 20-yrs, i.e., a rate of +0.15 °C/yr (extreme).

The last scenario should be considered as the extreme scenario. As calibration of the glaciers parameters was based solely on observed streamflow data, we only analyzed simulated streamflows and not, for instance, on variations in glaciers' area. In each scenario, the temperature was raised gradually every year. Rise in temperature increases the quantity of snow and ice melt in the glaciated areas and thus augments the streamflows. However, the impact decreases from upstream to downstream, as (i) enhanced contribution from rainfall dilutes flows from glaciated areas, and (ii) increased temperature also leads to greater evapotranspiration in the plains and thus smaller streamflows. As contribution from glaciated areas is mainly during the high flow season, the increase in streamflow occurs predominantly during the high flow season of June- September. Although, there is little modification during the lean flow season, melting of snow and ice starts earlier (in April) and ends later (in November). Such a phenomenon is likely to create more flood events and of higher magnitude, whether in the Upper Ganga or in the mountainous sub-basins of Devghat and Tehri dam (Table 35.3). Such a perceived change is of great consequence for the water infrastructure and the water security in these regions.

However, on a long-term basis the combination of glacial retreat, decreasing ice mass, early snowmelt and increased winter streamflow suggest that climate change is already affecting the Himalayan cryosphere (Kulkarni et al. 2007). Reduced surface runoff will reduce groundwater recharge and affect groundwater dynamics in the

Table 35.3 Simulated average change in annual streamflow at selected locations of the Ganga basin when temperature increases gradually over 20 yrs (as compared to the reference scenario)

Scenarios	Change in annual streamflow, km ³ /yr					
	Tehri dam (Sub-basin n°1)	Haridwar (Sub-basin n°2)	Narora (Sub-basin n°3)	Tajewala (Sub-basin n°8)	Delhi (Sub-basin n°9)	Farakka (Sub-basin n°53)
+1 °C over 20 yrs	+0.6 (+8%)*	+1.9 (+6%)	+1.8 (+8%)	+0.2 (+2%)	Negligible	+4.2 (+1%)
+2 °C over 20 yrs	+1.2 (+17%)	+3.9 (+13%)	+3.6 (+15%)	+0.3 (+4%)	Negligible	+8.8 (+3%)
+3 °C over 20 yrs	+1.9 (+26%)	+6.0 (+20%)	+5.4 (+23%)	+0.4 (+5%)	Negligible	+13.4 (+4%)

region, which will be critical in the western region, where most irrigation is from groundwater.

The extra water from the glaciated areas in the short to medium term presents a set of potential opportunities and some serious threats in the form of floods and water congestion especially in the eastern part of the basin. These potential flooding threats can be converted into improved water security through basin wide interventions like UTFI and the GAMES.

35.5 Underground Taming of Floods for Irrigation (UTFI)

The analysis of flood duration suggests that the majority of floods in the Ganges basin are relatively short with an average duration of between 3 and 5 days. Flood durations of 20–60 days have occurred 20 times and there were 7 floods of over 60 days during the period of 1985–2011. The 2007–2008 floods in India and Bangladesh had the longest duration which is explained by abnormal heavy rains during the monsoon season. These floods cause heavy damages to crops, assets, livestock and human lives and need to be mediated for water security and livelihood resilience.

UTFI is a specific and unique application of managed aquifer recharge (MAR). It adds new value to often ad-hoc MAR efforts and puts it into larger scale perspective that offers a wider range of benefits to both upstream and downstream areas. Central to UTFI is distributing recharge-enhancing interventions across strategic parts of the basin to provide supplies to meet additional demand during the dry season, and for this water to be recovered via agricultural wells and tubewells rather than allowing surface water to concentrate and be problematic in the lower floodplain areas of the basin.

The Ganges River basin where problems related to seasonal flooding, groundwater depletion and food and water security are particularly serious and likely to exacerbate due to climate-change induced impacts was selected for development of the opportunity assessment. Factors influencing the occurrence and impacts of floods in the Ganges were identified based on flood-risk mapping, groundwater development and mapping of groundwater potential zones. Across the Ganges basin, the maximum inundation was highly variable with an area varying from 6,000 to 11,000 km². Results show that 24% of the inner basin had very high suitability for UTFI (Fig. 35.2, Brindha and Pavelic 2016). The Suitability Index (SI) distribution reveals differentiation in suitability across the landscape- not all areas have the same potential to support UTFI implementation. There was a tendency for the watersheds at the periphery to have a low SI and these upland areas contribute runoff that can lead to flood inundation downstream.

Ramganga sub-basin is one of the area with generally high potential for UTFI implementation. In a drainage area of 18,665 km², there are about 20 million people living in the sub-basin. As in other parts of the basin, the most challenging water resources management issue in this sub-basin is the difference between water demand and seasonal availability. During monsoon months, there is widespread flooding and

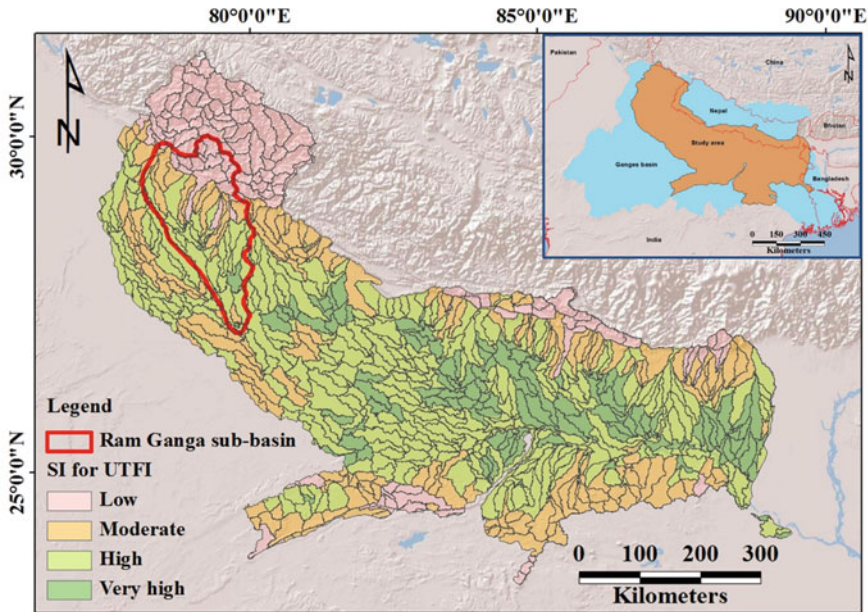


Fig. 35.2 Suitability Index (SI) rankings for the UTFI across the inner Ganges River Basin determined at the watershed level. The study site was located in the Ramganga sub-basin

during rest of the year, surface water flows are limited and groundwater levels are dropping across the basin. Flow-flood relationships showed that a 50% reduction would reduce flow of the highest magnitude with a recurrence interval of 16 yrs down to 2 yrs. For the 50% target, across the entire sub-basin, about 1,741 m³/ha would need to be intercepted, stored and recharged. For this to be achieved, and assuming a minimum infiltration rate of 10 m per wet season, less than 2% of the land area would need to be dedicated to recharge interventions across the entire Ramganga sub-basin.

A pilot trial of this concept was established in the Jiwai Jadid village of Moradabad district in the sub-basin. As the area is intensively cultivated and land is costly and scarce, the ponds within the village situated in local depressions, where there was scope to propose conversion of land for floodwater recharge became the obvious choice. Deep infiltration methods, which bypass the upper layers that are resistive to flow were used to transfer water directly under gravity to deeper more permeable layers. A set of 10 gravity-fed recharge wells with six-inch inner diameter PVC pipes slotted at the base were sunk into the bottom of the pond. The wells were coupled to a recharge filter consisting of gravel in a small brick masonry chamber as shown in Fig. 35.3 (Pavelic et al. 2015). Based on the initial testing of the performance of the recharge well, the anticipated recharge rates could be as high as 432 m³/day. Apart from improved livelihoods from enhanced irrigation, UTFI could be an effective means of disaster risk reduction when implemented at a larger scale. Though it is



Fig. 35.3 UTFI pilot site at Jiwai Jadid village, Ramganga sub-basin. India

too early to conclude from limited observations from the 2015 recharge season, the preliminary results from the pilot site shows an impressive improvement in the local groundwater table. Additionally, opportunities and risks of UTFI are being studied to provide the necessary degree of confidence for scaling up. It appears that there is enormous potential to apply the approach to help decision makers when planning investments in climate change adaptation and flood risk reduction to improve the water security in the Ganges and similar other basins.

35.6 Cranking up the Ganges Water Machine

Though the Ganges River Basin has abundant water resources, seasonal monsoon causes a mismatch in supply and demand which is likely to widen due to climate change impacts. Recurring floods and droughts associated with climate variability are common in the land and waterscape of the basin. The floods in the monsoon season (June to October), and of prolonged dry periods in the non-monsoon season (November to May) are serious concerns for the basin water security. More than 75% of the process depletion (evapotranspiration) from the irrigation, domestic and industrial sectors, in the basin at present 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.

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

- pumping water before the monsoon for depleting consumptively, in the irrigation and other sectors, to create an additional sub-surface storage in the Basin, and
- using carefully planned recharge structures to recharge the sub-surface from the monsoon runoff. The cycle of pump-recharge-pump increases storage for run-off water, which mitigates the impacts of floods and droughts.

Initially, the GWM envisaged capturing about 115 Bm³/yr of monsoon runoff in sub-surface storage and irrigating about 38 Mha of cropland. However, over the last 40 yrs, that estimate of gross irrigated area has already been realized (Amarasinghe et al. 2007). As a result, some areas are experiencing falling groundwater tables (Chinnasamy 2017). In the Ganges river basin, demand for irrigation is low during the Kharif season, but high in the Rabi and hot-weather seasons. Rainfall meets only 30% of the total monthly consumptive water use between November and March. The crop evapotranspiration requirements are very high in April and May. Because of the gap between water supply and crop water requirement, the actual irrigated area at present is substantially lower than the potential. A recent analysis by Amarasinghe et al. 2016 showed that the application of GWM concept is possible partially in some sub-basins (above Ramganga confluence, upper Chambal, Kali Sind, Upstream of Gomti, Ghaghara confluence to Gomti confluence, Tons, lower Yamuna), and fully in others (Bhagirathi, Damodar, Gandak, Ghaghara, Gomti, Kosi, and Son). Due to the patterns of irrigation requirement, the additional irrigation in the Rabi and hot weather seasons has the highest potential for depleting groundwater resources and creating subsurface storage. The potential unmet demand under the two scenarios ranges from 59 to 119 Bm³. However, due to supply constraints in some basins, the available water resources can meet only about 45 to 84 Bm³ which is quite significant. A preliminary ex-ante benefit and cost analysis, which captures the potential gains and losses after implementing a project, show that the GWM is a financially viable intervention with a benefit to cost ratio of over 2.3. However, the actual realization of its potential depends on several other hydrological and socio-economic factors. Using solar energy for groundwater pumping, which is financially more viable than using diesel for groundwater pumping as practiced in many areas now shall help in better realisation of the twin targets of reducing floods and enhancing water security and the livelihoods.

35.7 Conclusions

- i. The Ganga basin is one of the largest and most populous river basins in Asia with a population of more than 655 million. Topographic contrasts in the basin are the largest compared to any other basin which cause serious flooding in the

- downstream sub-basins. The Ganges basin has a total of 1,020 large glaciers and mean annual precipitation varies significantly throughout the basin. Rainfall pattern and glacier melt will be further impacted by the impending climate change.
- ii. The experimental glacier module of the WEAP model as applied to the Ganges basin showed that the contribution of glacier and snow melt decreases from upstream mountainous sub-basins to downstream flat sub-basins, with a magnitude variation of 75 to 3%. The glaciated areas contribute to streamflow predominantly during the wet period of June to September, i.e., when flows are actually already high, and glaciers are apparently a buffer against inter-annual variability of rainfall. The impact of climate change through temperature rise of 1 to 3 °C over a period of 20-yrns on the streamflow across the river course would be significant upstream causing serious flooding impacts but also presenting an opportunity for resource augmentation.
 - iii. ‘Underground Taming of Floods for Irrigation’ is a useful approach which involves interventions at the river basin scale to strategically recharge aquifers upstream during periods of high flow, thereby preventing local and downstream flooding and simultaneously providing additional groundwater for irrigation during the dry season. The pilot trial of UTFI was encouraging and indicated an enormous potential to help decision makers when planning investments in climate change adaptation and disaster risk reduction in the Ganges basin.
 - iv. The Ganges River Basin has abundant water resources, but seasonal monsoon causes a mismatch in supply and demand which shall be further accentuated due to climate change. Cranking up of the ‘Ganges Water Machine’ shall provide additional sub-surface storage through accelerated use of groundwater prior to the onset of the monsoon season, and subsequent recharging of this sub-surface storage through monsoon surface runoff. There is a potential unmet water demand of 59–125 Bm³/yr under different scenarios of irrigation water use and GWM can satisfy this demand up to 45–84 Bm³ in the selected sub-basins, and thus in the Ganges basin.

References

- Alford D, Armstrong R (2010) The role of glaciers in stream flow from the Nepal Himalaya. *Cryosphere Discuss* 4:469–494
- Amarasinghe UA, Shah T, Turrall H, Anand BK (2007) India’s water future to 2025–2050: business-as-usual scenario and deviations. In: IWMI Research Report 123. Colombo, Sri Lanka: International Water Management Institute (IWMI)
- Amarasinghe UA, Muthuwatta L, Smakhtin V, Surinaidu L, Natarajan R, Chinnasamy P, Kakumanu KR, Prathapar SA, Jain SK, Ghosh NC, Singh S, Sharma A, Jain SK, Kumar S, Goel MK (2016) Reviving the Ganges water machine: potential and challenges to meet increasing water demand in the Ganges River Basin. In: Colombo, Sri Lanka: International Water Management Institute (IWMI) IWMI Research Report Vol. 167, p. 42

- Brindha K, Pavelic P (2016) Identifying priority watersheds to mitigate flood and drought impacts by novel conjunctive water use management strategies. *Env. Earth Sc.* 75(5):1–17
- Chinnasamy P (2017) Depleting groundwater-an opportunity for flood storage? A case study from part of the Ganges river basin. India. *Hydrology Research* 48(2):431–441
- ICIMOD (2009) Climate Change in the Himalayas. Monthly Discharge Data for World Rivers, International Centre for Integrated Mountain Development, Kathmandu, Nepal, p 4
- Immerzeel WW, Van Beek LPH, Bierkens MFP (2010) Climate change will affect the Asian water towers. *Science* 328(5984):1382
- IPCC 2007 Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment report of the Intergovernmental Panel on Climate Change. (Eds.) Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL Cambridge: Cambridge University Press, U.K
- Jain SK, Agarwal PK, Singh VP (2007) Ganga Basin. Hydrology and Water Resources of India, Water Science and Technology Library, Springer, Heidelberg, Germany, pp 333–418
- Kulkarni AV, Bahuguna IM, Rathore BP, Singh SK, Randhawa SS, Sood RK, Dhar S (2007) Glacial retreat in Himalaya using Indian remote sensing satellite data. *Curr Sci* 92(1):69–74
- Miller JD, Immerzeel WW, Rees G (2012) Climate change impacts on glacier hydrology and river discharge in the Hindu Kush-Himalayas: a synthesis of the scientific basis. *Mt Res Dev* 32(4):461–467
- Revelle R, Lakshminarayana V (1975) The Ganges water machine. *Science* 188:611–616
- Pavelic P, Brindha K, Amarnath G, Eriyagama N, Muthuwatta L, Smakhtin V, Gangopadhyay PK, Malik RPS, Mishra A, Sharma BR, Hanjra MA, Reddy RV, Mishra VK, Verma CL, Kant L (2015) Controlling floods and droughts through underground storage: from concept to pilot implementation in the Ganges River Basin. In: Colombo, Sri Lanka: International Water Management Institute (IWMI) IWMI Research Report Vol. 165, p. 33
- Rikiishi K, Nakasato H (2006) Height dependence of the tendency for reduction in seasonal snow cover in the Himalaya and the Tibetan Plateau region, 1966–2001. *Ann Glaciol* 43(1):369–377
- Sharma BR, de Devraj C (2013) Opportunities for harnessing the increased contribution of glacier and snowmelt flows in the Ganges basin. *Water Policy* 15:9–25
- World Bank (2013) Ganges strategic basin assessment: a regional perspective on opportunities and risks. D.C., The World Bank, Washington
- Yates D, Sieber J, Purkey D, Huber-Lee A (2005) WEAP21 – A demand-, priority-and preference-driven water planning model. Part 1: model characteristics. *Water International* 30:487–500