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Assessment of long-term hydrogeological changes and plausible solutions to manage hydrological extremes in the transnational Ganga river basin

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Abstract

The Ganga is an international transboundary river that flows across three major riparian countries: India, Nepal, and Bangladesh, where India shares a significant proportion of the total basin area. The river system is highly dynamic and regularly floods in all three countries due to abundant rainfall in a short period of only four months each year that causes tremendous loss of both property and human life. In this study, we have done a synoptic review to synthesize the hydrology, hydrogeology, and modeling studies that have analyzed hydrological changes and their impacts in the Ganga basin. This review also identifies some of the knowledge gaps and discusses possible options for enhancing the understanding of sustainable water development and management. This review indicated that transparent data sharing, use of satellite-based observations along with *in-situ* data, integrated hydro-economic modeling linked to reliable coupled surface–groundwater models, a central shared decision support center for early warning systems to deal with hydrological extremes, joint river commissions and monitoring teams, and multilateral water sharing treaties (agreements) are required to promote sustainable and equitable distribution of water resources and to avoid water sharing conflicts in the Ganga basin.

Key words: climate change, delta, flooding, Ganga basin, groundwater, river migration

Highlights

- River system of Ganga basin is highly dynamic and regularly flooding the riparian countries.
- Groundwater contribution to river flow especially in lean period has declined.
- Mapping of paleo channels for potential recharge zone to store flood water could be a good option.
- Transparent information sharing and common decision support system may help for hydrological disaster management.

INTRODUCTION

The Ganga river flows across three major south South Asian countries: Nepal, India, and Bangladesh, and supports the livelihoods of more than 600 million people (Sharma *et al.* 2010; Amarasinghe *et al.* 2016a). The basin is highly fertile with abundant water resources and has immense cultural diversity,

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historically rich, and home to many flora and fauna (NMCG 2017). A significant share of the water is used for agriculture, supporting socio-economic activities, and agriculture-based income generation. Since the 1850s, irrigation interventions have become significant, such as the upper and lower Ganga canals to promote agriculture (Kaushal *et al.* 2019). In the basin, more than 85% of people depend on agriculture for their livelihoods (Sharma *et al.* 2010). During the last six decades, the Ganga basin has undergone substantial hydrogeological and socio-economic changes (Babel & Wahid 2011; Kumar 2017). Rainfall in the basin has reduced by 11.25% from 1951 to 1959 compared to 1991–2000, while evapotranspiration has only reduced by 3.61% (Agarwal 2014). Simultaneously, any change in river flows/abstractions compromises the integrity of broader ecosystem functions (Richter & Thomas 2007), leading to tremendous pressure on basin water resources (Sharma *et al.* 2010).

The surface water supply in the basin is highly seasonal, and close to 80% of the surface runoff is generated during the monsoon months from June to September. The river flows are regulated substantially by various dams, barrages, and diversion canals (Bandyopadhyay 1995). The stream flows in snow-fed areas have increased due to rising temperatures, and flows in nonperennial streams have declined due to anthropogenic activities (Ananda *et al.* 2018).

The infrastructure development and abstractions have affected the river flow regimes everywhere and are associated with impacts that compromise the integrity of the ecosystem functions (Richter & Thomas 2007), mainly below the Farakka barrage (Mirza 1998). Those changes, in turn, have reduced water availability, water quality, and water for navigation and downstream riverine ecosystems (Kala 2018). The basin is also prone to floods, droughts, and seismic hazards. Over geological time, natural hydrological processes, extreme events, and tectonic activity have shifted the course of some rivers several kilometers from their older paths (Sinha *et al.* 2005). The downstream outlet of the Ganga river has been steadily shifting eastward towards the Brahmaputra over the last several thousand years (Allison 1998). These shifts have significant implications on both surface and groundwater hydrology in the basin and water availability. For example, new river courses may increase groundwater recharge and increase water accessibility at new places, which can cause floods at new places, and at the same time, substantial groundwater potentials may be developed in paleochannels (see below). Conversely, the reverted flow through older channels abandoned several centuries ago may result in severe flooding, for example, upstream in the Indian state of Bihar and the Terai in Nepal, the Kosi river recently temporarily reverted to flowing through an old river and this led to the displacement of millions of people (Dixit 2009).

Although the Ganga basin is rich in water resources, the water resources are currently under extreme pressure (World Bank 2012). The rapidly increasing population and urbanization, improper management of groundwater, and indiscriminate waste disposal threaten the ecosystems of the Ganga basin (Misra 2011; MacDonald *et al.* 2015). The middle Ganga plain (Kanpur to Allahabad) is heavily industrialized and is the most polluted stretch of the river (Jain & Singh 2020), which has reduced river flows in the non-monsoon, and land-use changes have led to further degradation (Santy *et al.* 2020). Declining groundwater levels, reduced surface water flows in the non-monsoon, and deteriorating water quality, and increased salinity intrusion in the coastal aquifers are significant to present-day concerns in the basin (Bandyopadhyay 1995; Mirza 1998; Afroz & Rahman 2013). Furthermore, climate change can exacerbate the hydrological problems in the Ganga basin (Sharma *et al.* 2010; Nepal & Shrestha 2015). It is considered that climate change is going to increase monsoon flows with frequent flooding and increased availability of water for groundwater recharge (Whitehead *et al.* 2015).

This synoptic review synthesizes the hydrology, hydrogeology, and modeling studies that have analyzed hydrological changes and their impacts in the basin. It also identifies the knowledge gaps and discusses possible options for enhancing the understanding of sustainable water development and management.

METHODS AND DATA

The report synthesizes all published literature that describes the long-term hydrogeological changes in the Ganga basin since 1980. The present synthesis has been restricted to only water quantity issues in the basin. The list of prominent studies that have been carried out on the Ganga water resources and hydrogeology is provided in the list of references. Groundwater depths were collected from www.Indiawris.com, DEM data were downloaded from http://asterweb.jpl.nasa.gov.asp, and rainfall data were downloaded from the Indian meteorological department (www.imd.com). The spatial and temporal distributions of rainfall and groundwater level data were analyzed using the ArcGIS platform. The nonparametric sequential Mann–Kendall test was applied to rainfall data to detect the trends (Mann 1945; Kendall 1975). The general overview of geographical and hydrological conditions are summarized in the section 'Overview of the Ganga basin'. In the section 'Hydro-geomorphological changes', hydro-geomorphological changes, groundwater trends, groundwater–surface water interactions, climate change, ecological flows, and associated challenges are presented. Possible strategies for the management of hydrological disasters and restoration of groundwater resources are discussed in the section 'Possible strategies for improving the water resource status of the river Ganga' and the 'Discussion'.

OVERVIEW OF THE GANGA BASIN

The Ganga is one of the largest and highly populous river basins in the world. The river, which partly originates at the Gangotri glacier in Uttarakhand in India at an elevation of 7,016 meters above mean sea level (AMSL), drains in four major riparian countries, namely, India, Nepal, Bangladesh, and China, covering a total area of 1.05 million km^2 (Sharma *et al.* 2010) (Figure 1). The river Ganga traverses about 2,500 km from Gangothri to the mouth at the Bay of Bengal. It consists of many large

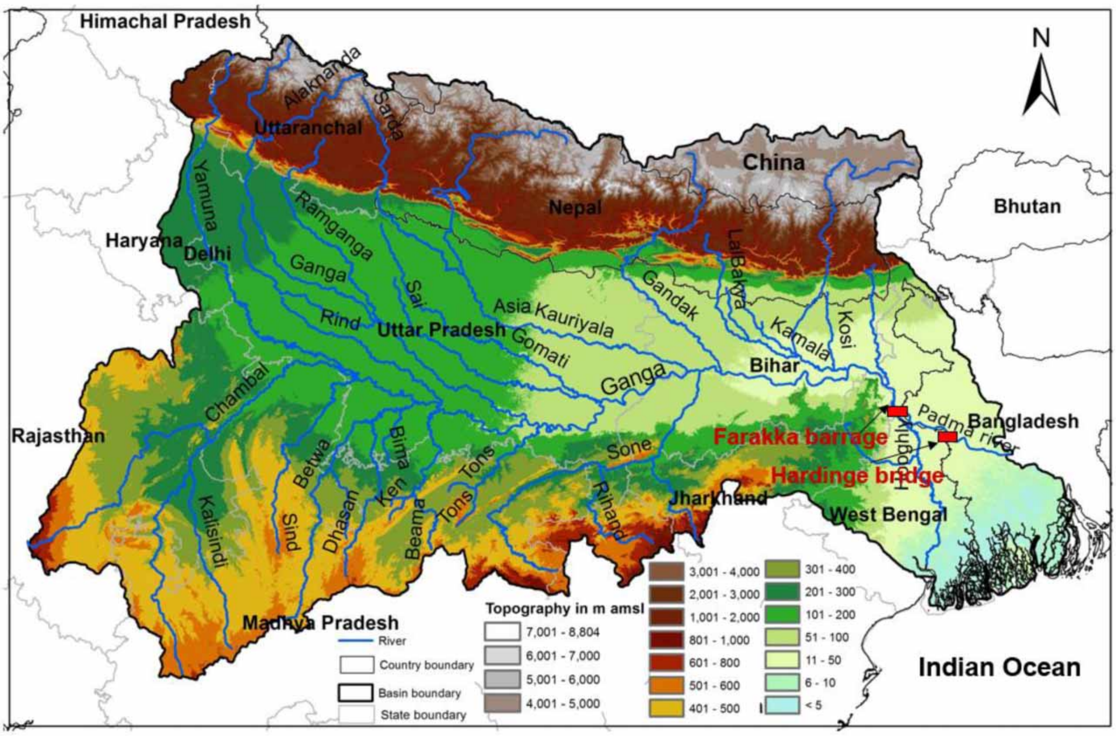

Figure 1 | Digital elevation (m AMSL) model with major rivers in the Ganga basin (date source is 30 m resolution SRTM data downloaded from: https://earthexplorer.usgs.gov/).

tributaries such as Yamuna, Mahakali, Karnali, Gandaki, and Kosi and Mahananda converge at different parts that increase the flow downstream (GOI 2014). In the downstream, the river divides into two streams in a location about 40 km below Farakka. The east flowing stream is a branch called the Bhagirathi-Hoogly, which continues to flow southwards and reaches the Bay of Bengal (Sinha *et al.* 2005). The west stream is called the Padma, which flows eastward into Bangladesh. The Padma joins the Brahmaputra and Meghna rivers in Bangladesh and creates the largest deltaic mangrove ecosystem in the world. In the non-monsoon, the majority of the flows are generated from the melting of Himalayan glaciers and partly from groundwater base flows from the aquifers (Moors *et al.* 2011).

Nepal's average surface water resource is estimated to be 198.2 billion cubic meters (Bm^3)/year, and groundwater storage is estimated as 81.7 Bm^3 (Amarasinghe *et al.* 2016b). Nepal's entire nation has been divided into five river basins from west to east: Mahakali, Karnali, Gandaki, Kosi, and the southern river basins. The surface water discharges to India from these rivers are presented in Table 1. The average annual available surface water in the whole Ganga basin in the Indian part is 525 Bm^3, of which 250 Bm^3 is utilizable. The surface water contribution from different distributaries to the main Ganga in India is discussed by Pun (2004), Hosterman & McCornick (2009), and GOI (2014).

Table 1 | Surface discharge from Nepal river basins to India in the Ganga basin

River basins	Flow in Bm^3/year
Southern rivers	65
Mahakali	15
Nepal tributaries	3
Karnali river	43.9
Gandaki	50.7
Kosi	47.2

Sources: Wells & Dorr 1987; FAO 2011.

The total mean annual surface water flow entering into the Bangladesh region is about 360 Bm^3/year, of which about 100 Bm^3 is from the Ganga with most of the rest from the northern (Himalayan) tributaries. About 70–80% of Bangladesh's annual flows are in the monsoon months of June to October and comprise approximately 100 Bm^3 (Amarasinghe *et al.* 2016a).

All riparian countries in the basin have abundant groundwater resources (Table 2). The net annual available groundwater volume is 232 Bm^3 and the annual groundwater draft is 139.53 Bm^3. Of the total groundwater draft, about 90% is utilized only for irrigation in the Ganga basin, with only a small fraction (10%) used by industries and domestic use. However, there is considerable spatial and temporal variability in groundwater development in the region. In India's driest areas (Rajasthan, Haryana, and Delhi), groundwater development is more than 100%. The low groundwater ($<$40%) development in Bihar, Uttar Pradesh, and West Bengal indicates that this resource remains mostly exploited (Table 2). The groundwater development in Nepal is about 10%, and in Bangladesh is 45% (Hussain *et al.* 2002; BMDA 2004; WECS 2004; BADC 2007; Jain *et al.* 2009; CGWB 2011). The overall contribution of recharge and discharge from Indian states, Nepal, and Bangladesh is presented in Table 2.

These data indicate that natural groundwater discharge in the non-monsoon months is 13.28 Bm^3 (as in the year 2011) flowing into the rivers as base flows in the Indian part of the Ganga basin. Natural discharges from Uttar Pradesh and Bihar aquifers to the rivers are known to be significant. Apart from the replenishable groundwater resources, there is a substantial static groundwater resource in the basin. It is estimated that 8,300 Bm^3 of groundwater resources are present in the Indian Ganga

Table 2 | State/Countrywide renewable and static groundwater resources availability, utilization, and groundwater development in Bm^3

		Available renewable groundwater resource			Available static groundwater resource			Groundwater withdrawals			
State/Country	**Average annual rainfall (mm)**	**ARGR**	**NDNM**	**NAGW**	**Alluvium**	**Hard Rocks**	**Total**	**Irrigation**	**Domestic and industries**	**AAGD**	**SGD %**
India											
Bihar	1,232	28.63	2.42	26.21	2,557	11	2,568	9.79	1.56	11.36	43
Jharkhand	917	5.96	0.55	5.41				1.17	0.44	1.61	30
Delhi	712	0.31	0.02	0.29	3	0	3	0.14	0.26	0.4	138
Haryana	615	10.48	0.68	9.8	420	1	421	11.71	0.72	12.43	127
Himachal Pradesh	1,340	0.59	0.06	0.53	13	0	13	0.23	0.08	0.31	58
Madhya Pradesh	917	33.95	1.7	32.25	14	27	41	16.66	1.33	17.99	56
Rajasthan	504	11.86	1.07	10.79	115	13	128	12.86	1.65	14.52	135
Uttar Pradesh	1,279	75.25	6.68	68.57	3,470	30	3,500	46	3.49	49.48	72
Uttarakhand	1,523	2.17	0.1	2.07				1.01	0.03	1.05	51
West Bengal	2,074	30.5	2.92	27.58	1,625	1	1,626	10.11	0.79	10.91	40
	Sub total	169.2	13.28	155.92				99.57	9.56	109.15	
Nepal	1,500	NA	NA	11.5				0.8	0.3	1.1	10
Bangladesh	2,600	NA	NA	64.6				25.2	4.1	29.3	45
	Total	169.2	13.28	232.02	8,217	83	8,300	125.57	13.96	139.53	

Compiled from CGWB (2011).

ARGR, annual replenishable groundwater resource; NAGW, net annual groundwater availability; AAGD, annual groundwater draft; SGD, stage of groundwater development; NDNM, natural discharge during non-monsoon; NA, not available.

aquifers; 99% of the groundwater resource is hosted in alluvium aquifers, and only 1% is in the hard-rock aquifers (Table 2).

Topography

The Ganga has a very complex topography (Figure 1). Mountains dominate the north with Mount Everest peaking at 8,848 meters (AMSL). The flat plains, at less than 100 m AMSL, dominate the middle part of the basin. The elevation falls to less than 5 m AMSL for most of the downstream parts. The Deccan Plateau covers the south of the basin and comprises elevated hills up to 1,200 m AMSL. The south-eastern part of the basin is a flat delta characterized by the extensive and delicate Sundarbans mangrove systems with an elevation of less than 5 m AMSL (GOI 2014).

Climate and rainfall

The Ganga basin has very diverse climate zones, ranging from arid, semi-arid, sub-tropical, tropical, temperate to alpine. The average temperature in the basin during the winter season (November to February) is between 5 and 30 °C. It sharply rises during summer (March to May) from 30 to 45 °C. The long-term average temperatures in the basin show a rising trend with 0.04 °C/year in Nepal and 0.091 °C/year in Bangladesh, which is much higher than the increase in global average temperatures (Mirza *et al.* 2003; Kirby *et al.* 2013). The average annual rainfall in the Indian part of Ganga varies from less than 400 mm in the western regions, 1,200 mm in the middle to more than 2,000 mm in the eastern parts (Figure 2(a)). The trend analysis of annual rainfall from 1980 to 2019 for the Indian part of Ganga basin shows a declining trend (Figure 2(b)). The average annual rainfall in Nepal is 1,860 mm (Mirza 1997), and in Bangladesh is 2,300 mm (Kirby *et al.* 2013). Trends from 1970 to

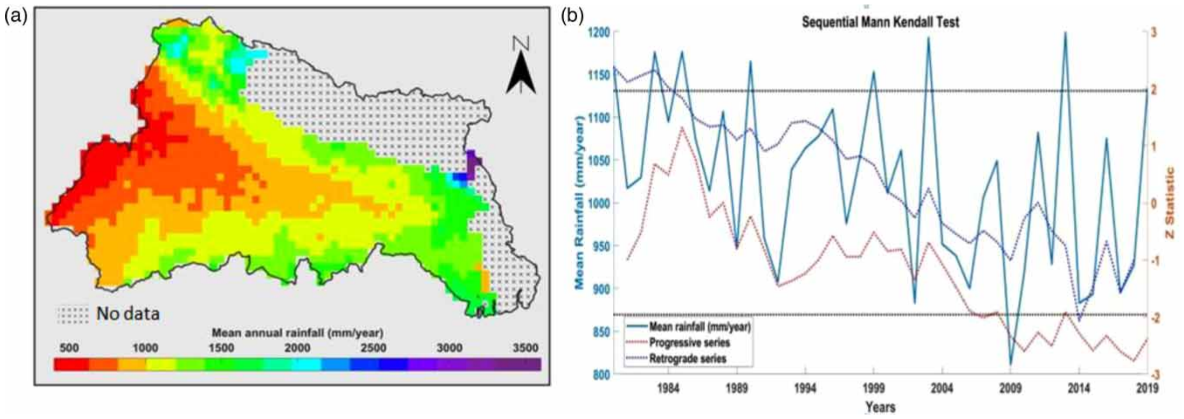

Figure 2 | (a) The distributed annual average rainfall in the Ganga basin from 1980 to 2019 and (b) annual rainfall trend from the year 1980 to 2019 (data source: www.imd.gov.in).

2010 show a declining trend of rainfall patterns in both Nepal and India (GOI 2014). Trends in rainfall in Bangladesh show increasing monsoonal rains in the north and west, but a decreasing pattern in the east (Kirby *et al.* 2015). The average annual recharge for Ganga basin in India ranged from 143 to 264 mm/year during 1996 to 2015 and experienced rapid declines in recharge rates in the basin with high temporal variations (Bhanja *et al.* 2019).

Geology and hydrogeology

The Ganga basin contains various types of geological formations from the Holocene, Quaternary, and Precambrian ages, from upstream hills down to the Bay of Bengal (Misra 2011). The north to the south of the basin can be divided into the Himalayan region, sub-Himalayan region, Bhabar zone, Terai zone, central Ganga plains, and marginal alluvial plains. The subsurface of the aquifer system is highly complex and depends on depositional features and geomorphologic characteristics.

Hydrogeologically, the basin is filled with thick alluvial sediments deposited by the river and its distributaries. It forms a thick set (varies from 1,500 to 2,000 m bgl (below ground level)) of unconfined and leaky aquifers with varying proportions of sand, gravel, and pebbles with several layers of high-yielding aquifers (Prasad 1994; MacDonald *et al.* 2015). A few rocky exposures can be seen in the basin margins (north, west, and north-east) (CGWB 2011). The principal aquifer in the Bangladesh part of the basin is either semi-confined or consists of stratified/interconnected, unconfined water-bearing zones (Sharma *et al.* 2010).

HYDRO-GEOMORPHOLOGICAL CHANGES

Geomorphologic changes and challenges

The Indo-Ganga basin was formed during the India-Eurasian collision process that was initiated in the Paleogene, and it is one of the largest active river basins in the world (USGS 2011). The basin filling and delta building accelerated its momentum during the late Holocene period (0.126 million years ago) when the Himalayan glaciers reduced, contributing large sediment loads (Rudra 2018). Due to the continuing rise of the Himalaya, the rivers draining the Ganga basin have formed a massive conduit of sediment of about 1 billion tons/year transfer from the Himalaya to the Ganga delta with extreme variability in terms of climatic parameters, geomorphic setting, hydrological regime, and tectonic activity (Milliman & Ren 1995). This has resulted in variable stratigraphic development across the plains along an east-west transect.

The upper Ganga plains have deeply incised rivers with 15–30 m of cliff sections along the river banks. The middle Ganga plains are characterized by an aggradation regime and 25–30 m thick sand/mud intervals. Significant variation in sedimentary architecture between the upper and middle Ganga plains in the western and eastern parts of the basin reflects geomorphic diversity-related precipitation gradients and tectonic history in the frontal orogenic (Sinha *et al.* 2005).

- Due to tectonic activity, climate, and other hydrogeological influences, the river courses have shifted several kilometers from their original path (Geddes 1960; Mookerjea 1961).
- The dynamic nature of the Kosi channel and its migration was observed in the 1960 to 1990 s (Arogyaswamy 1971; Wells & Dorr 1987; Agarwal & Bhoj 1992). In fact, between 1736 and 1950, the Kosi river shifted westwards across north Bihar by some 140 km (Hill 1997). Furthermore, in some years, the course has shifted by several kilometers.
- The Gandak river has shifted 80 km from west to east (Mohindra *et al.* 1992).
- Several small rivers such as Bhiri Handak, Baghamati, and Kamla-Balan in the Gandak-Kosi have also changed their positions by several kilometers (Phillip *et al.* 1989; Sinha *et al.* 1996; Jain & Sinha 2004).
- The Ghagra river in the Utter Pradesh plains had course shifts of about 5 km on either side of the active channel from 1975 to 1982 (Tangri 1992; Srivastava *et al.* 1994).
- The Ganga-Ramganga confluence point shifted downstream by about 20 km between 1911 and 2000 (Roy & Sinha 2007).
- The dynamic nature of river channels, caused by sedimentological readjustments or other tectonic factors, diverts flows into newly formed channels, often with low bank full capacity. The annual peak discharges often exceed mean annual flood and hence the river channels with low back full capacity with high discharge variability, and high sediment flux causing severe floods in the basin, particularly in the eastern part of Ganga, such as Bihar Kosi (Sinha 1998; Sinha & Jain 1998; Jain & Sinha 2003).

Changes in surface water flows and challenges

The major hydrological extremes in the basin are from both high flows causing floods in the wet season and low flows, leading to ecological drought in the non-monsoon. The major flood-prone areas are Uttar Pradesh, Bihar, West Bengal in India, and north-western parts of Bangladesh. Much of the floods are due to spilling and breaching embankments in the northern tributaries of Kosi and Mahananda and heavy local rainfall (http://india-wris.nrsc.gov.in). Floods have caused 36,744 crore Indian rupees (~8.25 billion USD in 2010 prices) of damage to agriculture and other infrastructure between 2000 and 2012 in India alone (GoI 2014).

In addition to the natural hydrological extremes, large-scale surface diversions have also created hardships in riparian countries (Mirza 1997). The surface water storage (dams/reservoirs) capacity has also been increased to 4.2 to 60 Bm^3 in the basin (GoI 2014). All these factors collectively show negative impacts on basin hydrology. For example, commissioning of the Farakka barrage in 1975 to divert the flows of about 30 Bm^3 into the Bhagirathi-Hoogly stream to restore the navigability of Kolkata port has caused significant hydrologic changes in the Ganga river system in Bangladesh, especially the non-homogeneity of the annual peak flows of the Ganga river (Abbas 1984; Mirza 1997).

The average (1960–2012) observed total annual surface water discharge at Farakka, before and after the barrage's commissioning, is shown in Figure 3 and Table 3 (GoI 2014). The data in the table show that the ratio between wet and non-monsoon flow is 7:1. The diversion has resulted in a decline of non-monsoon flow at Farakka by 33% that has accelerated the siltation problems in the Gorai river

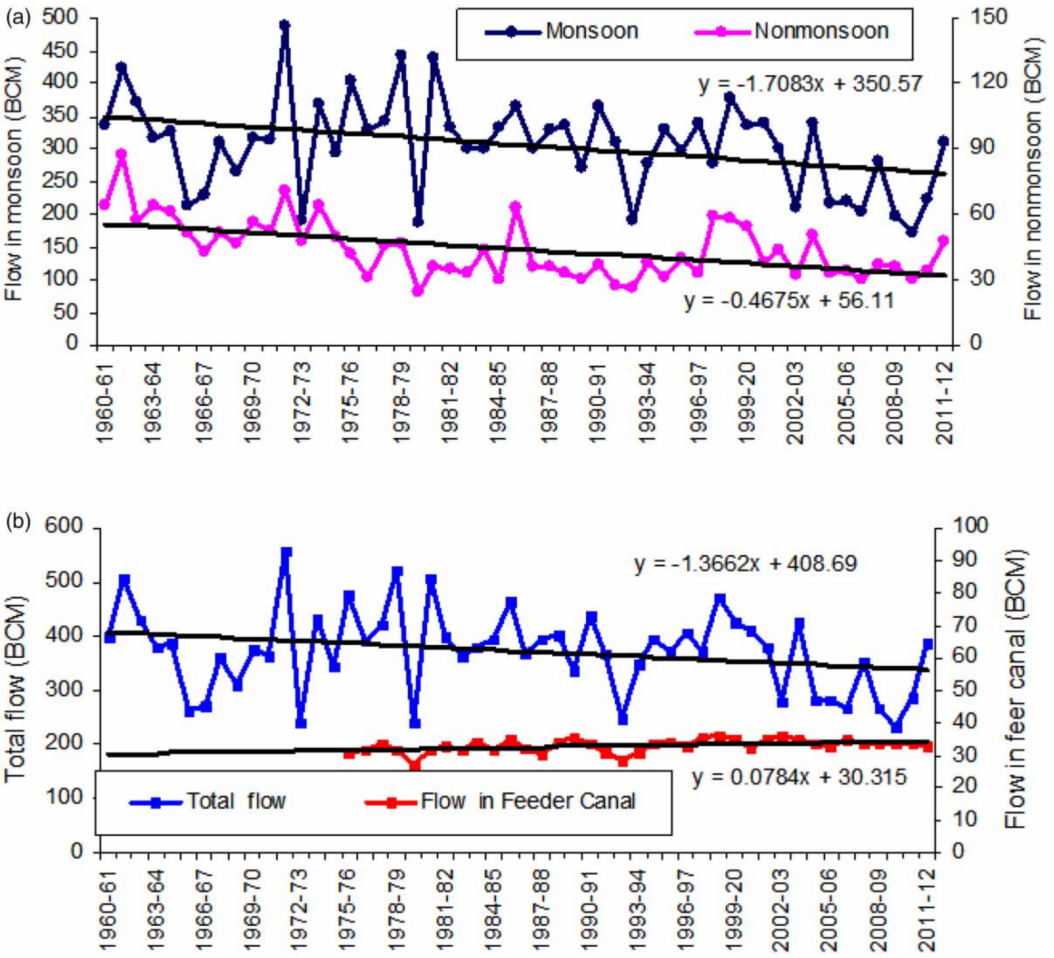

Figure 3 | (a) Surface water flows at Farakka from 1960 to 2012 in monsoon and non-monsoon and (b) total flow and flow in Bhagarathi-Hoogly feeder canal.

Table 3 | Long-term average surface water discharge (Bm^3) at Farakka before and after the Farakka barrage construction in 1975

Year	Monsoon	Non-monsoon	Flow in feeder canal	Total flow
1960–1975	317	57		375
1975–2012	300	38	33	372
Decline in flow (%)	5.3	33.3		0.08

(Mirza 1997), and increased frequency of floods up to 53% during monsoon and a drastic decline in non-monsoon flows in Bangladesh (Afroz & Rahman 2013). Due to this, the north-western part of Bangladesh is facing critical problems that include a water supply crisis, seawater intrusion, crop and grain damage, soil erosion, deforestation, and depletion of wildlife that provide challenges in achieving ecological, social, fisheries, forestry, livelihoods, and economic balances in terms of sustainable development (Khan *et al.* 2014; Hassan 2019). After the Ganga 1996 water treaty (agreement) for water sharing between India and Bangladesh, Bangladesh receives a mostly fair share of flow (Khalequzzaman & Islam 2012). Nevertheless, Bangladesh argues that they do not receive their fair share of water allocated for them in the non-monsoon. Rahman *et al.* (2019) indicated that the treaty underestimated the impact of climate variability and possibly increased upstream water abstraction creating obligations for guaranteed flows perpetuating the risk of water-sharing conflicts.

On the other hand, India and Nepal signed the Kosi agreement in 1954 to construct a barrage between the India–Nepal border to regulate the flow of the river, flood management, power generation, and irrigation purposes. Nepal argues that it did not get a fair deal in terms of the benefits of the barrage (Malhotra 2010). The review of Malhotra (2010) on water conflicts between India and Nepal shows that Nepal is not satisfied and expressed concerns that they did not receive fair benefits with other treaties, including the Sharada Dam construction (1927), Gandak Agreement (1959), Tanakpur Agreement (1991), and the Mahakali Treaty (1996). In most cases, lack of trust, no joint river commissions, and lack of fair, open data sharing in the Ganga basin are hampering the ability to arrive at mutually beneficial water allocation and sharing agreements.

Groundwater trends and challenges

The Ganga basin forms one of the largest groundwater reservoirs with a multi-aquifer system down to depths of 2,000 m bgl (CGWB 1996). The dependency on groundwater is being increased to meet the needs of the rising population, industrialization, and urbanization, and that also makes the aquifers more sensitive to water depletion, degradation of water quality, and reduction in base flow contributions, which are essential for non-monsoon river flows (GRBMP 2014). The long-term groundwater table data in the north-western states (Delhi, Madhya Pradesh, Haryana, and Rajasthan) of the Ganga basin show declining trends (CGWB 2014).

The number of tube-wells has increased exponentially in all the metro cities (Delhi, Kolkata, Kanpur, Lucknow, Patna, Agra, Meerut, Varanasi, and Allahabad) in India (CGWB 2011), Katmandu in Nepal and Dhaka in Bangladesh to meet the increasing demands of water that has led to the depletion of groundwater levels. The depths to groundwater for the year 2018 in the Indian part are presented in Figure 4, and the data show that shallow depths to groundwater (<50 m bgl) are observed in the foothills of Nepal, and deeper depths to groundwater (>50 m bgl) are observed in Delhi, Lucknow, and Jaipur for both pre- and post-monsoon seasons. During the last four decades, the number of groundwater-overexploited blocks has increased from 118 to 680 from 1984 to 2009 in the Indian part of Ganga (Table 4). At the same time, the natural discharge (base flows to the rivers) has declined to 13.28 Bm^3 from 16.37 Bm^3 between 2004 and 2009 (CGWB 2011).

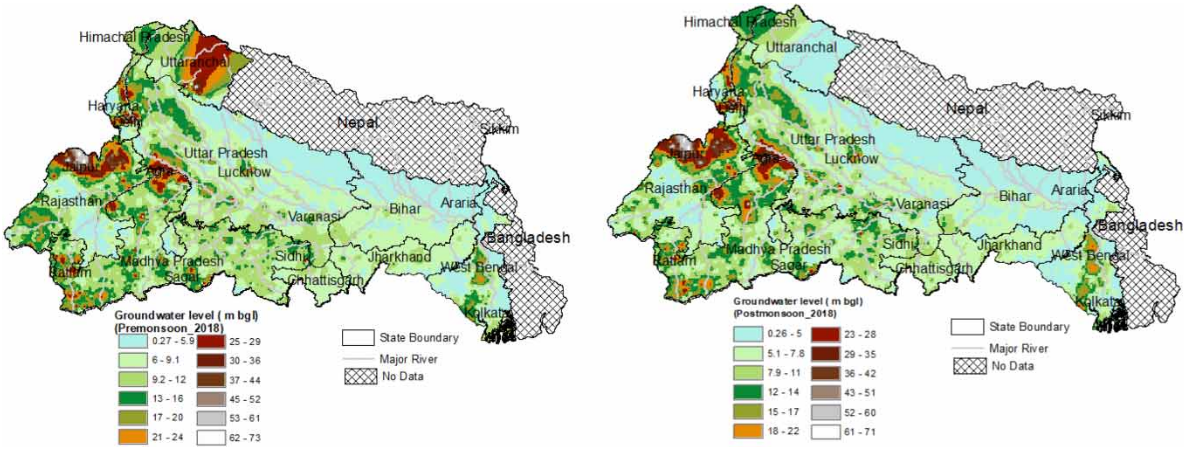

Figure 4 | Pre- and post-monsoon groundwater levels in the Indian part of the Ganga basin for the year 2018 (data source: www.india-wris.com).

The lack of a sufficiently well-distributed *in-situ* surface water and groundwater monitoring network and hydrogeological data (e.g., aquifer properties data such as specific yield and hydraulic

Table 4 | Number of over-exploited blocks in the Indian part of the Ganga river (here over-exploitation refers to more groundwater pumping than recharge)

		Over-exploited blocks			
State	**Total number of blocks**	**1984–85**	**1992–93**	**2003–04**	**2008–09**
Uttarakhand	97	NA	NA	5	6
Uttar Pradesh	821	53	31	138	215
Madhya Pradesh	459	0	3	48	89
Bihar	534	14	1	Nil	Nil
Jharkhand	260	NA	NA	Nil	Nil
Rajasthan	236	21	56	204	207
West Bengal	341	NA	NA	38	38
Haryana	127	31	51	71	98
Himachal Pradesh	75	NA	NA	Nil	2
Delhi	27	NA	NA	7	25
Total	2,977	119	142	511	680

conductivity, and the spatial extent and vertical distribution of different aquifers) is hampering the proper assessment of water resources in the Ganga basin for its proper management for sustainable development.

NASA's Gravity Recovery and Climate Experiment (GRACE) twin satellites offer an opportunity to map total water storage (TWS) at a 400 × 400 km grid resolution. TWS comprises groundwater, soil water, surface water, snow, and ice. Groundwater storage (GWS) can be obtained by subtracting independent estimates of surface water and offline (land-only) model estimates of soil water, snow, and ice from TWS to understand the groundwater conditions where *in-situ* observations are limited in time and space. GRACE observations have been used to estimate groundwater depletion rates worldwide (Famiglietti & Rodell 2013). Many researchers have used GRACE observations and reported depletion trends of GWS in the Indian subcontinent (Rodell *et al.* 2009; Tiwari *et al.* 2009; Panda & Wahr 2016; Bhanja *et al.* 2016). In particular, Shamsudduha & Panda (2019) have observed the declining trends (>10 mm/year) of groundwater elevations based on monthly TWS anomalies from 2003 to 2014 in the Ganga and Brahmaputra basins. GRACE-derived assessments of GWS vary substantially and have not been reconciled with *in-situ* observations in the Brahmaputra, Ganges, Indus, and Meghna river basins (Shamsudduha & Panda 2019), that may be due to poor observation network and data sharing constraints. Hydrological models are required, which are calibrated with *in-situ* observational data to estimate current water balances and understand the projected impacts of climate and humans. However, Scanlon *et al.* (2018) have reported that all global hydrological models, including the Ganga basin, underestimate the water storage changes compared to GRACE-derived TWS trends. Groundwater depletion or accumulation is determined by the interaction of rainfall, canal leakage, abstraction rates, and reduced base flows in rivers due to induced recharge and reduced natural discharge of the aquifers to partially offset the demands of the Ganga basin (MacDonald *et al.* 2016). In areas with shallow clay layers, shallow 'perched' water can become disconnected from deeper groundwater-bearing units when groundwater elevations have dropped because of overpumping. In the Ganga basin, most of the monitoring wells are very shallow, and therefore can only monitor upper aquifer units or perched water tables (Bons 2018). Hence, shallow groundwater monitoring data might indicate rising water tables as irrigation increases, while at the same time, the deeper aquifer groundwater volumes can be depleting. This may be a reason for disagreements between *in-situ* observations and GRACE-derived estimations in the Ganga basin. Hence, it is preferable to use satellite-derived estimates coupled with detailed *in-situ* monitoring data at a range of depth profiles for improved data assimilation and modeling.

The average groundwater elevations have declined by −1.5 m in the northern part of Katmandu valley, −5.9 m in the central region, and −5.3 m in the southern part from 2001 to 2009 (Ganesh 2011). The same declining trend is observed in the Barind tract of Bangladesh (Rahman & Mahbub 2012). The river stage heights have been depleted by −0.5 to −38.1 cm/year from 1999 to 2013 in the non-monsoon season due to base flow reduction of around 59% caused by irrigation pumping from 1970 (Mukherjee *et al.* 2018). As a result, groundwater depletion (Rodell *et al.* 2009) has created an unviable nexus between water and energy (Scott & Sharma 2009).

The declining trends of groundwater elevations during the wet season, particularly in the north-western and central part of Bangladesh, indicate that the shallow aquifers are not being fully recharged in the monsoon period (Rahman & Roehrig 2006; Shamsudduha *et al.* 2009; Rahman & Mahbub 2012; Kirby *et al.* 2013). Groundwater elevations are falling in many urban areas, particularly in large groundwater-dependent cities, such as Dhaka city in Bangladesh (MacDonald *et al.* 2015).

In the Meghana estuary and southern coastal part of Bangladesh, groundwater elevations rising trend is observed to be about 0–0.1 m/year due to sea-level rise (Shamsudduha *et al.* 2009). The initiation of the Barind Multipurpose Development Project (BMDP) in 1986 for poverty alleviation through the introduction of unique groundwater-based irrigation in Bangladesh has accelerated groundwater use (Bhuiyan 1984; Ahmad *et al.* 2014).

The number of shallow and deep tube-wells has increased greatly after the BMDP, and pumping from these has resulted in a decline of pre-monsoon groundwater elevations to >25 m from <10 m; however, in the post-monsoon, these aquifers are fully replenished due to higher rainfall recharge (Shahid & Hazarika 2010; MacDonald *et al.* 2015). This observation is crucial as it indicates that the Ganga alluvial aquifers can restore the aquifer's resources with proper management of the recharge mechanisms.

Groundwater and surface water interactions and challenges

The interactions between surface and groundwater are primarily driven by hydrological, hydraulic, and geomorphological processes (Prasad 1990). The Ganga basin contains alluvial soils in 58% of its total area with higher hydraulic conductivity (K), and transmissivity (T) values favorable for increased percolation/infiltration (recharge) of the water, meaning that these parts tend to have more significant surface water–groundwater interactions (Krishan *et al.* 2020). Due to the aquifer's high K and T ranges in Ganga (alluvium part of the basin), more recharge and seepages are expected. It is estimated that 32% of the total rainfall contributes to groundwater recharge (INRM 2013). A consequence of the hydraulic connectivity between surface waters and groundwaters can directly impact the pollutant loads and groundwater quality, in addition to groundwater contaminants being drained into surface waters in particular locations or times.

However, there is significant spatial variability in recharge and hydrogeological properties in the basin, which should be considered in water resource estimation and to analyze the hydrogeological processes (Bonsor *et al.* (2017). The study also suggested that streams/river leakage is the dominant recharge process rather than natural recharge (i.e., rainfall infiltration). It is evident that rivers/surface water and groundwater aquifers are in constant interaction in the Ganga basin. For example, the north Bihar plains (Prasad 1990), Ganga, and Brahmaputra flood plains (Shamsudduha *et al.* 2009), Ganga river and its small tributaries between Gomukh and Dabrani (Krishan *et al.* 2020) all have notable groundwater–surface interactions. These rivers, acting as effluent (losing streams) are contributing recharge to the aquifer and receiving a substantial contribution (gaining streams) of their lean flows through groundwater discharge, all along with their courses in monsoon (Prasad 1990). A considerable quantity of groundwater contributes to river baseflows in Bangladesh and India (CGWB 2011; Kirby *et al.* 2013). In the Ganga-Brahmaputra basin, about 200 Bm^3 of recharged water flows to the sea as baseflows (Basu *et al.* 2001), which is about 14% in total available average annual flow (1,400 Bm^3). The reduction in water flows and water spread (flow in different tributaries and canals) areas in northwest Bangladesh tends to reduce recharge, leading to a decline in groundwater levels, an increase in salinity levels, and loss of biodiversity in the delta (Islam *et al.* 2017). Sustainable groundwater supplies are constrained by extensive contamination due to both anthropogenic (biological) and geogenic (arsenic) contamination rather than depletion of groundwater levels (MacDonald *et al.* 2016).

Maheswaran *et al.* (2016) have identified losing streams and gaining streams in the Ganga basin using groundwater modeling with Visual MODFLOW that may help regulate pumping rates where gaining streams become losing streams. CGWB (2015) has constructed a groundwater flow model for the middle Ganga plain with detailed aquifer layers obtained by heliborne and groundwater-based geophysical investigations. This study explained the water interactions among the different aquifer units and their role in groundwater elevations and storage. The Ganges water machine proposed by Revelle & Lakshminarayana (1975) shows that a massive subsurface storage potential and an increase in pumping near rivers can increase induced recharge. Their concept shows that increased groundwater pumping before the monsoon can deplete the aquifers (creating storage space in the aquifer) and create hydraulic gradients from rivers to aquifers that could recharge the aquifer during the rainy seasons. Nevertheless, in recent years, it is evident that groundwater levels are generally being depleted, base flows have declined, and under this scenario, their proposal needs to be revisited or updated. Surinaidu *et al.* (2016, 2017) noted that distributed recharge and pumping by identifying suitable locations could be a good option instead of pumping only near rivers. Muthuwatta *et al.* (2017) showed (by taking Ramganga (a sub-basin of Ganga) as a case study) that subsurface storage could increase lean flows using hydrologic modeling with a Soil Water Assessment Tool (SWAT). Alam *et al.* (2020), assessing the impact of pilot-scale village-level recharge wells, which primarily get water during monsoon, has shown that a significant increase in groundwater recharge would support up to 18 hectares of irrigation in the Ramganga sub-basin. van der Vat *et al.* (2019) constructed a basin-scale integrated hydrological model with a participatory approach, and their study results show that rapid socio-economic development in the basin is going to increase demand for water and result in high pollution loads. The study also suggests investments in water storage, reduced water demands, and wastewater treatment combined for sustainable economic growth and healthy ecology in the basin. Whitehead *et al.* (2015) have further predicted a significant impact on water quality at the downstream end of the Ganga in different future socio-economic scenarios, and the study indicated a less sustainable future due to high population growth, enhanced atmospheric nitrogen deposition, the tremendous land-use change that includes indiscriminate urbanization and intensified irrigation, and increased water abstraction.

Climate change impacts on the hydrology of the Ganga basin

The countries situated in the Ganga basin are among the most climate-vulnerable nations in the world. The projected climate models indicate that the monsoon precipitation might increase in the future (Immerzeel *et al.* 2010; Kumar *et al.* 2011; Pervez & Henebry 2014; Lutz *et al.* 2014), although the magnitude of the projected change varies, primarily due to differences in the driving global climate models (GCMs) and the study domains (Nepal & Shrestha 2015). The hydrological balance in the Ganga basin is expected to alter due to climate change associated with rising temperatures, uncertain changes in precipitation pattern and glacier melt, intensified monsoons, water-induced disasters, and sea-level increases that give rise to new water management challenges (Jeuland *et al.* 2013). The impacts of climate change on water resources are likely to affect irrigation and the environmental flows in non-monsoon and power generation (Gosain *et al.* 2011). For example, the studies carried out by Zhou *et al.* (2019) in the four sub-basins in the Ganga basin, namely, Chambal, Damodar, Gandak, and Yamuna indicated water availability would increase by 13%, 33, 21, and 28%, respectively, in these four sub-basins by the year 2050 when compared to the year 2010 under the greenhouse gas Representative Concentration Pathway (RCP) scenario 4.5. However, distribution will not be even throughout the year; for example, Yamuna will have 25% less water in the non-monsoon by 2050.

Significant increases in monsoon flows may increase flood risk (Uhe *et al.* 2019) and also reduce flows with extended drought periods between 2050 and 2090, and will have negative impacts on water and sediment supply, seawater intrusion, and irrigated agriculture, and for maintaining crucial ecosystems such as the mangrove forests, with serious implications for people's livelihoods (Jeppesen *et al.* 2009). Nepal's hydropower potential is projected to be very high across climate models due to annual flow in the tributary rivers, greatly exceeding the storage capacities of existing reservoirs, including in dry scenarios (Jeuland *et al.* 2013). On the other hand, an increase in temperature may demand more water for the cooling requirements for power plants, for example, about 40% of existing and planned thermal power plants in Damodar and almost all in Gandak and Yamuna will face high water risks in the future, endangering the energy security in India (Zhou *et al.* 2019).

Increased temperatures will also raise non-productive (surface water and soil moisture evaporation) evaporative losses from rivers, irrigation canals, and reservoirs. Higher temperatures will increase evaporation rates and hence enhanced crop water requirements in both irrigated and natural systems. The increased crop water demands can be met using available water supplies (precipitation or irrigation), but that will result in lower river flows. The increasing pressure and rising competition among the different water users may threaten the livelihoods of 85% of the population in the Ganges basin who rely on agriculture and will harm the basin's long-term sustainable development (Sharma *et al.* 2010).

The Ganga basin is certainly going to face ecological as well as socio-economic crises due to rising population, indiscriminate urban and industrial growth, the influx of enormous nutrients and other contaminants into the river, and climate changes associated with rising temperatures and irregular rainfall patterns (Tripathi & Singh 2013; Tripathi *et al.* 2016).

Climate change, together with land-use change, can have severe negative impacts on the Ganga river's aquatic life. For example, the study carried out by Santy *et al.* (2020) in the Kanpur region along a 238 km length of the Ganga river's most polluted stretch indicated eutrophic conditions due to high loadings of both urban and industrial contaminants. Climate change combined with higher organic and nutrient loads to the river can change the water's physico-chemical properties that will affect its biota (Mittal *et al.* 2014), fish population dynamics, diversity, and community structures and can lead to species invasion (Sarkar *et al.* 2012). Increases in minimum water temperatures coupled with pollution negatively impact native fish breeding and increase the assemblages of non-native fish (Das *et al.* 2013).

More extreme rainfall events may lead to more pollution loads in the basin (Whitehead *et al.* 2015). For example, dissolved arsenic and fluoride concentrations are mainly derived from soils/aquifer material weathering. Variations in the climate with resultant changes in pH and water temperatures may enhance these elements' leaching into water bodies (Wetzel & Likens 2000; Mittal *et al.* 2014).

Environmental flows (E-Flows)

E-Flows assessment is a relatively new field in developing countries like India. E-Flows refer to a minimum flow that is required to perform its natural functions such as transporting water and solids from its catchment, the formation of land, self-purification and sustenance of its various systems along with sustaining cultural, spiritual, and livelihood activities of the people or associated population (GRBMP 2011). The Wildlife Institute of India (WII) recommended required E-Flows to be 20% of monthly average flows during the dry period (November–March), 25% of monthly average flow for October and April, and 30% of the monthly average of high flows from May to September (Mathur *et al.* 2012). Most of the E-Flows in India are considered minimum flows as a fraction of either the mean annual flows or dry weather flows or ten daily average flows. For example, in India, Himachal Pradesh had issued a directive to allocate 15% of the minimum observed flow as environmental flows while Uttrakhand allocated 10% of lean seasonal flow (Kumar *et al.* 2007; Jain 2015). However, these allocations are not strictly based on empirical data or calculations. A literature review by Tharme (2003) reveals that globally, there are around 207 different methods for the assessment of E-Flows. Among those methods, the building block method (BBM) is recommended by WWF India (2012) and GRBMP (2011) for the Ganga basin due to its flexibility to be modified.

Tare *et al.* 2017 has estimated E-Flow for the upper Ganga reach at five different locations: Ranari (Dharasu), upstream and downstream of Devprayag, Rudraprayag, and Rishikesh, using a modified version of BBM for the lean period, for monsoon period and high floods based on the flow requirements of keystone species for different sites and geomorphic considerations. Their computation results recommended that for the wet period (mid-May to mid-October) monthly E-Flows vary from ~23% to ~40% of the monthly natural flows and for the non-monsoon (mid-October to mid-May), they range from 29% to 53%. Kaushal *et al.* (2019) explained that E-Flow allocation might be required to cut some of the flow in the total irrigation water requirement of the basin, and that may lead to an adverse impact on the farming community. However, Kaushal *et al.* (2019) suggested that E-Flow implementation required more water in the Ganga river stretches, and that could be achieved through improved irrigation efficiency and institutional framework. A recent study by Dutta *et al.* (2020) on the Ganga river indicated that river quality has improved in terms of increased dissolved oxygen (DO) and reduced biological oxygen demand (BOD), fecal coliform, total coliform, and nitrate (NO_3^-) concentrations following the nationwide lockdown due to the COVID-19 pandemic coupled with increased rainfall in 2020 of about 60% greater than average. These new data show that the river ecosystem's health could be quickly restored if specific changes occur in the basin.

POSSIBLE STRATEGIES FOR IMPROVING THE WATER RESOURCE STATUS OF THE RIVER GANGA

Several studies have assessed ways and means of simultaneously addressing floods and droughts, sustainable water use, and conflict resolution. Some approaches include the following:

- Creating subsurface storage, by increased pumping along the canals and rivers before the monsoon, and recharge the storage space created through monsoon flows and floodwater (Chaturvedi & Srivastava 1985; Khan *et al.* 2014). This approach can create an opportunity to store 60 Bm^3/yr of surface water in the subsurface and can generate 25 million hectares of additional irrigation potential (Surinaidu *et al.* 2016; Amarasinghe *et al.* 2016a).
- Constructing flood embankments or upstream big storage reservoirs to mitigate floods are not an economically feasible solution and can create massive disasters/create environmental problems and associated risks (Chamlagain 2009; Sadoff *et al.* 2013; Somanathan 2013; Xu *et al.* 2013). For example, such structures can reduce downstream lean flows and increase flood frequency. For example, downstream of Farrakka barrage and breaching flood embankments can create massive disasters. However, more interdisciplinary research is needed on this topic.
- Removing some pre-existing dams (and those that are planned for the basin should be carefully reconsidered) to restore the rivers' ecological flows where currently the flows are not sufficient to meet E-Flow requirements. For example, the USA has already removed nearly 500 dams to restore rivers and riparian habitats (Gleick *et al.* 2009).
- Implementing distributed pumping and recharge that is increasing pumping everywhere and recharge through managed aquifer recharge (MAR). This could help to store 90 Bm^3/year surface

water in the subsurface (Ala Eldin *et al.* 2000; Khan *et al.* 2014). Flood plains can be used to recharge groundwater by constructing barrages across the river to increase infiltration (Sone *et al.* 2009).

- Undertaking heliborne geophysical surveys. In recent years these have been shown to provide extensive spatial coverage of the subsurface that can help to identify aquifer structures and properties (Chandra *et al.* 2019). CGWB has initiated a pilot project on aquifer mapping aided by the heliborne geophysical technique in six different hydrogeological terrains of India that includes part of the middle Ganga plains situated around Patna, Bihar state (CGWB 2015). Those study results are still pending, but the technique will help cover a large spatial resolution area and depths of <250 m. The project aims to delineate the aquifer geometry, identify the type of aquifers and groundwater regime behaviors, and associated hydraulic characteristics for micro-level aquifer mapping that can enable the development of reliable groundwater flow models for better management. Recently, a paleochannel has been detected by CGWB and NGRI that joins the Yamuna river at Durgapur village, roughly 26 km south of the current Ganga-Yamuna Sangam at Prayagraj. It is considered that this channel could have a storage potential of 2.7 Bm^3 (NMCG 2020). As discussed above, sections of the Ganga river system are highly dynamic and have migrated several kilometers; the older channels could be used as floodwater storage reservoirs if located.
- Considering the hydrological boundary of the basin as a single unit and regulating river flows in the sub-basin by a central authority can help to increase water supply for downstream users below Farakka barrage in Bangladesh (Rogers & Kung 1985).
- Making multilateral treaties/agreements among all riparian countries in the basin to share the water resources can ease the tensions and better manage the hydrological problems (Moors *et al.* 2011).
- Collecting and sharing high-resolution groundwater data, including groundwater depths and quality from deep and shallow monitoring wells are required to understand the groundwater reserves and its predicting flow dynamics needed for reliable groundwater governance (MacDonald *et al.* 2015).
- Creating liberalized policies, such as an increased subsidy of electricity (Mukherji *et al.* 2009), or elimination of duty on diesel pumps, to promote groundwater pumping during the non-monsoon season in eastern Ganga regions may help agricultural and economic development due to huge groundwater potential.
- The depletion of groundwater elevations in the Ganga basin severely impacts the non-monsoon flows that endanger the many aquatic-riparian habitats; hence, multiple sectors with proper water quality criteria need to be considered for E-Flow assessment (Sharma & Dutta 2020).
- Improving irrigation and fertilizer application can increase crop yields and optimize water use, both in the current and under a projected future climate (Mainuddin *et al.* 2013). An integrated water management approach with cooperation of all riparian countries with good governance and high technology investment can foster regional development and overcome the severe water conflicts in the Ganga basin (Rahman *et al.* 2009; Babel & Wahid 2011).

At present, there are no detailed field study sites available to store surface water in the subsurface through distributed pumping with distributed recharge, which is one of the potential solutions (Sadoff *et al.* 2013). It is also not currently clear how much time is required to create subsurface storage and its recuperating capacity, the required energy/investments, and its economic feasibility and benefits for different ecosystems such as for irrigation, water quality, and increasing non-monsoon river flow. Particularly regarding the coastal riverine systems, the basin's geomorphology should be carefully evaluated and is yet to be fully characterized. It is critical to know the salinity encroachment and sediment load dynamics in the basin to protect its different ecosystems (Islam & Gnauck 2008). Increasing data sharing and transparency is the biggest management challenge in the basin. It is needed to find effective solutions to mitigate different hydrological problems. There are many bilateral agreements and joint river commissions between the countries to share the water resources, but there is currently a lack of a data-sharing framework.

DISCUSSION

The construction of large dams on the Ganga's upstream tributaries would have a limited impact on controlling downstream floods and irrigated agriculture in India. However, dams augment the low flows delivered by regulated storage infrastructures (Wu *et al.* 2013). Underground storage of monsoon water in the subsurface through distributed pumping and with distributed recharge through different artificial recharge mechanisms could be one of the best potential solutions, rather than big surface water storages, to combat all hydrologic disasters (Khan *et al.* 2014). For this, a detailed study that can assess the probability of rainfall, supported by land and water availability and the nature of the underlying aquifer formations, should be a pre-requisite. Local government agencies should take land and water management initiatives to guide and regulate these interventions without becoming overly bureaucratic or restrictive (Prathapar *et al.* 2012). For example, Pavelic *et al.* (2012) on the Chao Priya river basin in Thailand revealed that distributed managed aquifer recharge could capture 28% of coastal discharge from the basin, which could help reduce the intensity of both floods and droughts. It also indicated that floodwater harvesting once in four years is more than sufficient without significantly impacting other ecosystems and that investments made in managed aquifer recharge structures can be regenerated in seven years. Therefore, pilot-scale studies at the small watershed level to test the efficacy of different technologies and potential benefits before implementing at basin scale are needed. To achieve all of these, it requires notable policy reforms and a suitable energy-pricing environment, sufficient institutional capacity, and real changes in the farmers' attitudes to water resources (Sadoff *et al.* 2013).

Detailed integrated groundwater–surface modeling linked to hydro-economic models is also essential to understand complex hydrogeologic processes, evaluate the investments and energy requirements, and share their potential benefits of different interventions among the riparians for sustainable water resources management. For example, Wang *et al.* (2013) has applied integrated surface water–groundwater modeling with a coupled SWAT-MODFLOW framework to evaluate the hydrologic process and climate change for water resource management in Haih river basin, China. The results helped in quantifying the exchange of water between aquifer and streams with changing groundwater storage and water diversions under the influence of climate change in the basin. van der Vat *et al.* (2019) has done surface–groundwater modeling for the whole Indian part of the Ganga basin with a community participated modeling approach. The study suggested that economic growth and ecological health can be achieved only when combining investments in wastewater treatment and reservoir capacity with interventions that reduce irrigation water demand and increase non-monsoon river flows. In all cases, data abundance, accessibility, and quality are significant concerns; reliable data sharing and regional cooperation could improve the water management strategy.

Decision support systems tools can be developed with integrated numerical modeling tools linked with hydro-economic models such as in the Mekong river basin and the Rio Grande basin to solve national and transboundary water issues (Bach *et al.* 2011; GWP 2013). These analytical modeling tools can guide multilateral treaties (agreements) to provide important insights both for finding the best water-use solutions, help with sharing the water benefits among the riparian users, and improve water security for multiple purposes, both sustainably and equitably. It also facilitates integrated water resources management and the mitigation of extreme climate events such as floods and droughts. However, all modeling studies should address different uncertainties or assumptions involved in the modeling to inform policymakers' confidence levels to make the right decision for sustainable water resource management (Johnston & Smakhtin 2014). Also, joint data collection teams and joint river commissions for high-level negotiations may reduce the water conflicts in the basin. The satellite data, for example, Sentinel (https://sentinel.esa.int/web/sentinel/sentinel-data-access), Landsat (https://www.usgs.gov/core-science-systems/nli/landsat/landsat-data-access?qt-science_support_page_related_con=0#qt-science_support_page_related_con), MODIS (https://modis.gsfc.nasa.gov/data/), soil moisture missions (https://smap.jpl.nasa.gov/) and GRACE should be used along with *in-situ* observational data. Google Earth engine or any open source platforms can be used to obtain the required satellite data for the modeling and analysis along with *in-situ* observations (https://earthengine.google.com/).

CONCLUSIONS

In the Ganga basin, floods are driven by high topographical variations from water generating areas (Nepal) to water importing regions (India and Bangladesh) in the downstream, with low relief, very high local rainfall, and continuous changing river courses, and breaching of flood embankments. However, hydrological droughts are primarily due to the monsoon's failure/late start, unregulated water resources development, and regulations that are creating water sharing conflicts in the non-monsoon. The literature analysis indicated that upstream multipurpose dams to mitigate flood disasters and regulate non-monsoon water accessibility could have profound negative implications on the environment and other dependent ecological actors and only provide small benefits in the non-monsoon. Such infrastructure also requires a long time for development and huge investments for relatively low amounts of floodwater storage.

The decline in groundwater elevations in recent decades has had severe negative impacts on river water flows in the non-monsoon, and the reduced availability threatens food security, ecological sustainability and can increase the likelihood of water conflicts. However, the high storage capacity and percolation rates in the Ganga basin's alluvial aquifers can provide an ample opportunity to store excess surface water in the subsurface. The subsurface aquifer storage can be created by distributed pumping at planned times, and the created storage space can be refilled with distributed recharge that could reduce the intensity of floods and droughts. The proper utilization of river beds/flood plains can create great potential to store water through underground floodwater storage in the aquifers. Locating suitable sites to store water and maintain structures from siltation is challenging and requires detailed surveys and assessments. Identifying paleochannels by large-scale geophysical investigations such as the heliborne geophysical technique can be a promising option to store floodwater effectively and for the simultaneous creation of opportunities for different water-dependent ecosystems.

The implemented pilot-scale projects related to floodwater storage in the aquifers have already yielded local benefits by creating additional water for irrigation. To upscale these kinds of interventions at the basin scale, however, it is essential to develop fully integrated hydro-economic models linked to integrated hydrological models to help policymakers make decisions. Due to the current lack of reliable data on hydrological observations and the inadequate spatial coverage of hydrogeology data across the basin, remote sensing/earth observational data (in combination with reliable and available *in-situ* data for calibration) is needed. Remote sensing data can then be used in numerical models for making predictions.

The development of a basin-wide database, preferably open access/public, could help policymakers forecast and mitigate the Ganga basin's different hydrological problems. A collaborative knowledge base/research group on hydrological forecasting using this database can then advise policymakers to minimize the basin-wide problems. New multilateral agreements rather than bilateral agreements among the riparian countries could be more beneficial for equitable water-sharing, mitigation of extreme events, and ease of geopolitical tensions arising from the water distribution in the basin.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories (groundwater levels data: https://indiawris.gov.in/wris/ and rainfall data: www.imd.gov.in and groundwater data: www.cgwb.com).

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