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N. Rajmohan and S. A. Prathapar

International Water Management Institute

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Contents

Acronyms and Abbreviations

BADC	Bangladesh Agricultural Development Corporation
BGS	British Geological Survey
CGWB	Central Ground Water Board
DPHE	Department of Public Health Engineering, Bangladesh
DWSS	Department of Water Supply and Sewerage, Nepal
EGB	Eastern Ganges Basin
FAO	Food and Agriculture Organization of the United Nations
FMIS	Farmer-managed Irrigation Systems, Nepal
GBM	Ganges-Brahmaputra-Meghna
GDP	Gross domestic product
GoB	Government of Bangladesh
GWIB	Ground Water Information Booklet
GWRDB	Groundwater Resources Development Board, Nepal
GWTF	Ground Water Task Force, Bangladesh
HTW	Hand Tube Well
NRCS	Nepal Red Cross Society
STW	Shallow Tube well
WB	West Bengal
WBPCB	West Bengal Pollution Control Board
WHO	World Health Organization

Summary

The Ganges Basin is a part of the Ganges-Brahmaputra-Meghna (GBM) River Basin, draining 1,089,370 square kilometers (km^2) in Tibet (China), Nepal, India and Bangladesh, and is one of the most populated (600 million) river basins in the world with a population density of 550 persons/km^2. Most of the population is poor and rely on agriculture for their livelihoods. This study focuses on the Eastern Ganges Basin (EGB) and covers the states of Bihar, Jharkhand and West Bengal in India, and Bangladesh and the Nepal Terai. Poverty is acute in the EGB where household incomes are low, food security is not assured, and devastating floods (and also water shortages) occur too often, with particularly severe impacts on the poor. The floods are primarily caused by excessive rainfall in the steep hilly transboundary catchments, but the impacts of these floods can be reduced through wiser groundwater management that enhances the regulating services of the basin's natural and agricultural ecosystems. The Eastern Gangetic Plains is underlain by one of the most prolific aquifers in the world. Yet, farmers struggle to cope with dry spells and droughts because of their inability to access groundwater. The lack of understanding of physical processes deters our ability to manage the aquifer in such a way that floods and droughts can be minimized.

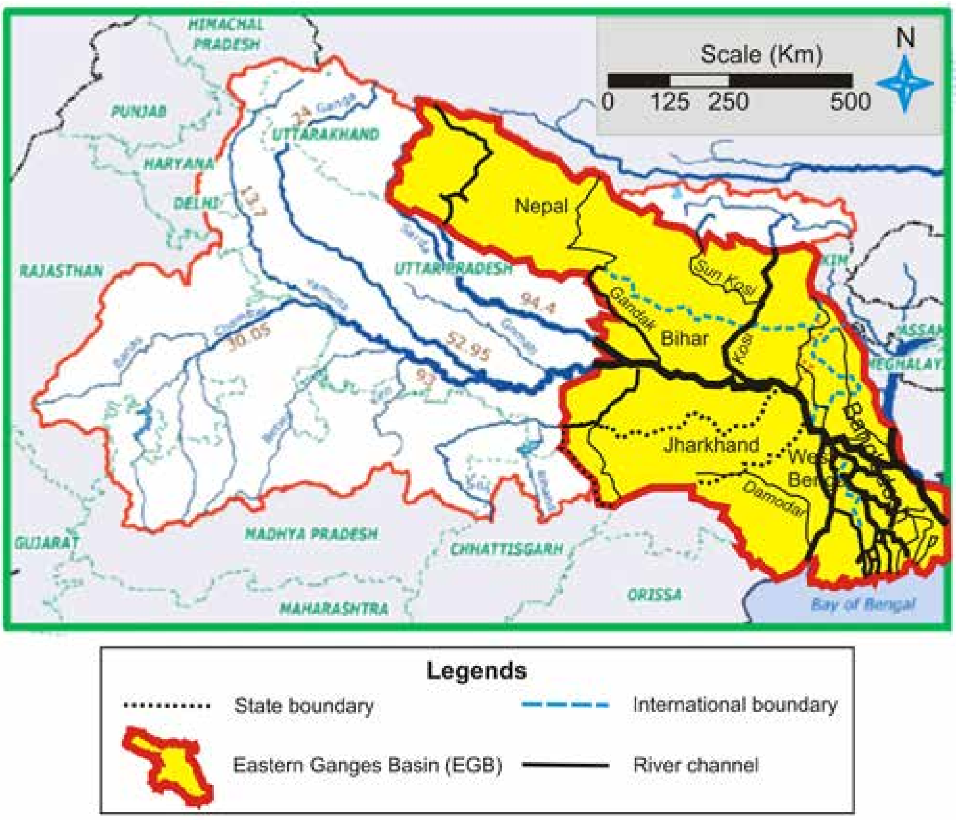
In the EGB, rainfall is highly variable in space and time due to various geomorphological features, and most of the rainfall occurs during the southwest monsoon (June to September). The major part of the EGB is covered by porous formation and groundwater occurs in unconfined, semi-confined and confined conditions. The annual replenishable groundwater resources in the EGB (Indian part) is 65.09 billion cubic meters (Bm^3) and net groundwater availability is 59.2 Bm^3 annually. Annual groundwater availability in Bangladesh and Nepal are 64.6 Bm^3 and 11.5 Bm^3, respectively. Overall, groundwater availability in the EGB is 135.3 Bm^3 and only 34.79% of this is utilized for irrigation. The stage of groundwater development in this region is 40%, which highlights that existing groundwater resources are not used appropriately and there is room for further groundwater development in the EGB. Further, enormous plains and fertile lands are also available for agriculture. Water quality is also an issue in a few parts of the EGB, especially due to arsenic, iron, fluoride and chloride contamination. However, proper planning and management will be required to utilize the surplus groundwater potential for agriculture, which will enhance food production and reduce poverty in the EGB. This report is an attempt to compile data available to form a base for future work related to groundwater development, management and modeling in this basin.

INTRODUCTION

The Ganges Basin is a part of the Ganges-Brahmaputra-Meghna (GBM) River Basin, draining 1,089,370 km^2 in Tibet (3.67%), Nepal (12.85%), India (79.2%) and Bangladesh (4.28%) (Figure 1). The Indus Basin and Aravalli Ridge are borders on the western side, and Vindhyas and Chotanagpur Plateau limit in the South. The Ganges merges with the Brahmaputra through the common distributaries into the Bay of Bengal in the East. The Ganges Basin is one of the most populated (600 million) river basins in the world with a population density of 550 persons/ km^2 (Jain et al. 2009). The average annual discharge of this river is 16,650 cubic meters per second (m^3/s) (Jain et al. 2009). This basin is covered by densely forested mountains in the South, semi-arid valleys in the North of the Himalaya, the scrubby Siwalik foothills and the fertile Gangetic Plains. Table 1 provides an overview of the physical characteristics of the Ganges Basin. A major part of the Himalayan region is covered by snow throughout the year. Infiltration is generally very high in this region due to fractures, fissures, openings, joints and bedding plans. Groundwater is in unconfined condition and exists in the secondary porosity. In the sub-Himalayan region, the aquifer is predominantly unconfined and sometimes semi-confined. It is estimated that there is 244.8 Bm^3 of groundwater available in the Ganges Basin (India, Bangladesh and Nepal) (Table 2).

The present study concentrates on the EGB to explore the hydrogeology and groundwater resource potential of this region, and documents the relevant data in these areas. The EGB covers the states of Bihar, Jharkhand and West Bengal in India, and Bangladesh and the Nepal Terai. The basin has a very high population density and 80% of the total population living in

FIGURE 1. Ganges and Eastern Ganges basins. The streamflow data is the annual average in cubic kilometers.



Source: After Harshadeep 2011.

the rural areas depend on agriculture for their livelihoods. Poor water management followed by small and fragmented landholdings, and poverty, are major challenges which reduces the productivity of various food crops in the EGB. The basin has a huge amount of surface water and untapped groundwater resources which are not properly utilized. Also, the EGB has a vast amount of fertile agricultural lands. Regulation, water access, low electrification, high cost of diesel and scattered landholdings are major constraints for improvements in agricultural productivity in this region.

A better understanding of the hydrogeology, and groundwater potential and availability of this region will help to create proper planning for groundwater management and governance to reduce poverty and assure food security. The aim of this report is to assist planners/policymakers in the planning and management of groundwater resources in the EGB, and ensure that the data available in this report will act as a base for any future work related to groundwater development, management, modeling, etc., in this basin. According to the knowledge of the authors, this is the first report that has been compiled with complete details of the hydrogeology and groundwater resource potential of the Eastern Ganges Basin. However, studies related to groundwater modeling and detailed groundwater quality issues are huge topics and not within the scope of the present study.

TABLE 1. Physical characteristics of the Ganges Basin.

Parameters	Ganges Basin
Length (km)	2,525
Drainage area (km^2)	1,089,370
Country	India, Nepal, Bangladesh, Tibet (China)
Population (millions)	600
Altitude range	7,010 meters (m) to the sea
Climate	Hot and sub-humid
Rainfall (mm)	up to 1,000 (western part), above 1,800 (eastern and lower part)
Mean inflow (Bm^3)	525
Irrigated area (Mha)	19.5
Sediment load (billion tons/year)	0.73 (at Farakka)
Erosion processes	*Himalaya*: Landslides, glaciation, channel, sheet and rill, glacial lake outburst floods (GLOFs), and landslide lake-burst floods (LLFs). *Siwalik*: Landslides, sheet and rill, channel. *Plains*: Sheet and rill, channel, wind.
Lithology	*Himalaya*: Crystalline, sedimentary, and metasedimentary rocks. *Terai Bhabar belt*: Boulder, cobble, pebble, gravels, sands, silt and clays. *Siwalik*: Sedimentary rocks, often partly lithified. *Plains*: Unconsolidated alluvium and aeolian deposits (clays and silts, gravels and sands, lenses of peat and organic matter, carbonate and siliceous concretions [Kankar]). *Floodplain and delta*: Aquifer of grey medium to course sands capped by10-60 m surface clay, silty clay, peat.

Source: After Jain et al. 2009.
Note: Mha = million hectares.

TABLE 2. Estimated groundwater availability and use in the Ganga Basin.

Basin	Groundwater availability (Bm^3)	Annual groundwater draft (Bm^3)			Stage of groundwater development (%)
		Irrigation	Domestic, industrial and others	Total	
India	168.7	94.4	8.2	102.4	61
Nepal	11.5	0.8	0.3	1.1	10
Bangladesh	64.6	25.2	4.1	29.3	45
Total	*244.8*	*120.4*	*12.6*	*132.8*	*54*

Source: After Jain et al. 2009; CGWB 2006; BADC 2007; BMDA 2004; Hossain et al. 2002; WECS 2004.

EASTERN GANGES BASIN

The present study focuses on the Eastern Ganges Basin and covers part of India, Bangladesh and Nepal Terai (Figure 1; Khunti, Simdega, West Singhbhum, East Singhbhum and Seraikela Kharsawan districts in Jharkhand are excluded). In India, three states (Bihar, Jharkhand and West Bengal) come under the EGB. Earlier studies have not demarcated the proper boundary for the Indian part (Jharkhand and West Bengal) of the Ganga Basin, and this varies according to different literature (Jain et al. 2009; Harshadeep 2011; Sharma and Prathapar 2013; http://gfcc.bih.nic.in/default.htm). Hence, the present study considers the complete states of Bihar, West Bengal and Jharkhand for discussion along with Bangladesh and Nepal Terai.

In 2011, the total population of this region was 391.21 million (Census of India, Bangladesh Bureau of Statistics, Central Bureau of Statistics, Nepal), which is 5.60% of the world population (6,974 million). From the total population, 80% live in rural areas and depend on agriculture for their livelihoods. Poverty is acute in EGB, where household incomes are low, food security is not assured and devastating floods (and also water shortages) occur too often, with particularly severe impacts on the poor. Floods are primarily caused by excessive rainfall in the steep hilly transboundary catchments, but their impacts can be reduced through wiser groundwater management that enhances the regulating services of the basin's natural and agricultural ecosystems. The Eastern Gangetic Plains is underlain by one of the most prolific aquifers in the world. Yet, farmers struggle to cope with dry spells and droughts because of their inability to access groundwater. The lack of understanding of physical processes deters our ability to manage the aquifer in such a way that floods and droughts can be minimized.

The EGB has huge groundwater potential which is not being completely utilized. According to CGWB (2011), the stage of groundwater development of Bihar (43%), Jharkhand (30%) and West Bengal (40%) are not exceeding 50%, which highlights the existence of enormous untapped groundwater potential. Likewise, the stage of groundwater development in Bangladesh and Nepal are 45% and 10%, respectively (Table 2). This highlights that the annual replenishable groundwater/net groundwater availability is not being completely utilized. The EGB contributes substantially to the food security of the countries in this region.

India

General

Bihar

The State of Bihar has an area of 94,163 km^2 and the total population was 103.80 million in 2011 (Census of India). Bihar has a tropical monsoon climate and it varies with its physiographic set-up. The overall average annual rainfall of this state is 1,232 mm. Bihar can be divided into three climate zones, such as the sub-Himalayan zone, the Ganga Plains zone and the parts of Chotanagpur Plateau zones of South Bihar (MoEF 2007). The sub-Himalayan zone (northern part of Bihar) receives a maximum rainfall of 1,400 mm and the average temperature varies from a minimum of 4 °C to a maximum of 43 °C. In the Ganga Plains, the mean minimum and maximum temperature is between 10 °C and 41.3 °C, respectively. In parts of the Chotanagpur Plateau, the annual rainfall is from 800 mm in the western part to 600 mm in the eastern region. Likewise, the maximum temperature also fluctuates depending on the region (46 °C in the West and 42 °C in the East). The River Ganga divided the Bihar Plain into two unequal halves, and flows through the middle from West to East. North Bihar, to the North of River Ganga, covers an area of 52,442 km^2 (Prasad 1990). Seven major rivers, the Mahananda, Kosi, Kamla, Bagmati, Burhi Gandak, Gandaki and Ghaghara, flow from the sub-Himalayan zone in the North and reaches the River Ganga. Average annual rainfall of North Bihar is 1,300 mm, of which 85% is received from the southwest monsoon (Prasad 1990).

Jharkhand

In Jharkhand, the geographical area is 79,714 km^2 and the total population was 32.966 million in 2011 (Census of India). The state has about 29,740 km^2 of agricultural area and 24% of forest area. In Jharkhand, about 70% of the population depends on the agriculture sector for their livelihoods (Water Resources Department, Government of Jharkhand 2011). The average annual rainfall varies from 1,063 mm (Godda District) to 1,575 mm (Sahibganj District) (GWIB-CGWB 2007). Rainfall in Jharkhand is highly variable and mainly occurs within the four-month period between June and September. This state experiences winter (November to February) and summer (March to mid-June). The annual average temperature ranges from 3 °C to 46 °C (GWIB-CGWB 2007). River Ganges is one of the major rivers in this state. Numerous rivers flow through this state, such as Swarnarekha, Sone, Barakar, Damodar, Ajay, South Koel, Shankh, North Koel, Mayurakshi, Brahmani, Bansloi, Gumani, Sakri, Panchanan and Phalgu, and these are tributaries of the River Ganga. However, the principal rivers are Damodar, Barakar, Koel and Swarnarekha, which make a large contribution to the agriculture sector in this region.

West Bengal

West Bengal has a total area of 88,752 km^2 and the estimated population of West Bengal was 91.35 million in 2011 (Census of India). The highest population (8.9 million) was recorded in North 24 Parganas District and Kolkata has 24,252 people/km^2. The Bhagirathi and Hooghly rivers originated from the Ganges and flow through West Bengal. West Bengal has wide topographic diversity from the North Himalayas to the south Bay of Bengal. The climate varies from tropical in the southern portions to humid subtropical in the north, and the state experiences four seasons (summer, rainy season, a short autumn and winter). The temperature varies from 38 °C to 45 °C during the summer. Monsoon rainfall during June to September is a major source of water, and average annual rainfall varies from 1,211 mm (Bankura District) to 3,067 mm (Cooch Behar District) (GWIB-CGWB 2007). West Bengal is divided into North Bengal and South Bengal by the River Ganga. Rainfall intensity in North Bengal (from Darjeeling to Malda District) ranges from 25.51 mm/day to greater than 44.51 mm/day. The northern part of the state experiences heavy rainfall (average annual rainfall greater than 2,500 mm/yr), especially in Darjeeling (2,841 mm), Jalpaiguri and Cooch Behar (3,067 mm) districts (GWIB-CGWB 2007). During winter (December to January), the temperature varies between less than 0 °C and 10 °C. Lowest temperature and occasional snowfall are noticed in the Darjeeling Himalayan hill region. In South Bengal, rainfall ranges from 25.51 mm/day to less than 21.51 mm/day (MoEF 2010). In addition to rainfall, the state receives water from Nepal, Bhutan (transboundary water) and across interstate borders via River Ganga and tributaries of the Brahmaputra River, such as Teesta, Torsa and Jaldhaka.

Geology and Lithology

Bihar

The major part of Bihar is covered with Indo-gangetic alluvium besides consolidated formations in the southern parts (CGWB 2011). Geologically, Bihar represents the extreme northern front of the Indian subcontinent, which includes the (i) belt of Himalayan foothills in the northern fringe of Paschim Champaran; (ii) vast Ganga Plains; (iii) Vindhyan (Kaimur) Plateau extending into Rohtas region; (iv) sporadic and small Gondwana Basin outliers in Banka District; (v) Satpura Range extending into a large part of the area north of Chotanagpur Plateau; (vi) parts of Bihar Mica belt in Nawada, Jamui and Banka districts; and (vii) Granite Gneissic complex of Chotanagpur Plateau (MoEF 2007). MoEF (2007) explains the geology and geographical distribution of Bihar in detail. Almost two-thirds of Bihar is covered by the Ganga Basin, composed of alluvium and masks the basement rocks. According to CGWB (2011), litho-units of Bihar are grouped as unconsolidated/alluvial formations, semi-consolidated formations and consolidated/fissured formations. Lithology of North Bihar shows that very deep alluvial deposits, from 1,500 to 2,000 m, with several layers of high-yielding aquifers exist in this region (Rao and Prasad 1994). These are in semi-confined and confined conditions, generally overlain by very thick unconfined aquifers.

Jharkhand

Jharkhand is underlain by a variety of rock formations from Pre-Cambrian to recent age. In Jharkhand, the predominant hard rocks comprise of Archaean metamorphics with associated intrusive and sedimentaries belonging to the Vindhyan and Gondwana super group with associated igneous rocks. Chotanagpur Granite gneiss is old Batholithic mass, covers the maximum part of the state and hosts various types of mineral (Directorate of Geology, Jharkhand). According to CGWB (2011), the major part of the state is covered by the formations comprising of granites, granite gneisses, metasedimentaries and a variety of volcanic rocks. Rajmahal traps, representative of volcanic formation, are exposed as patches in a linear fashion in the northeastern part. In the northwestern part of the state, the sediments belonging to the Vindhayan system are exposed. Patches of laterites are observed in the southwestern part. Recent alluvial formations are mostly confined to the valleys along major rivers of the state.

West Bengal

Based on the physiographic unit, West Bengal can be divided into four regions: (i) the Himalayan Region (Darjeeling, Jalpaiguri and Cooch Behar districts); (ii) Chotanagpur Plateau (which covers the district of Purulia and the western part of the districts of Bardhaman, Medinipur and Birbhum, and the northern part of Bankura); (iii) Deltaic zone (Sundarbans area of the South 24 Parganas and a small part of the North 24 Parganas); and (iv) the rest of the state being plains. Based on the hydrogeology, the state can be broadly classified into two units: (i) fissured hard rocks, and (ii) porous alluvial formations (CGWB 2008). Fissured formation is a hard-rock formation which includes crystalline, metasedimentary and volcanic rocks. Alluvial sediments occupy two-thirds of the state, and are deposited by the Ganga and Brahmaputra rivers. However, hard-rock formations are observed mostly in the western part of the state. For example, Purulia District is mostly underlain by Pre-Cambrian metamorphics (GWIB-CGWB 2007). Granites and granite gneisses are commonly encountered in this district. Likewise, Bankura District is partly covered by crystalline granite gneiss of Archaean age along with other formations such as sedimentary sandstone and shale of lower Gondwana age, and quaternary alluvium. The northwestern part of West Bengal (Darjeeling District) is covered by consolidated formations (Buxa group of metamorphic rock), semi-consolidated formations (Gondwana and Siwalik sedimentary formations) and unconsolidated formations (piedmont and alluvial deposit). The rest of the state is covered by thick alluvial formation. The sand and gravel horizons with different textures constitute the main aquifer.

Groundwater Potential and Challenges

Bihar

According to MoEF (2007), based on water-bearing properties, the geological formations of Bihar are classified into four main subdivisions: (i) main alluvial basin with good groundwater potential having a considerable granulose zone with effective porosity; (ii) marginal alluvial terrain, a part of the alluvial tract, is dominated by finer clastics or inadequate alluvial thickness and granular horizons fringing the hard-rock terrain and the localized alluvial pockets in the rocky terrain, viz., near rivers and in valleys (20-30 m of alluvium); (iii) hard-rock terrain, comprising the entire Archaean terrain and Vindhyan hill areas with very little groundwater potential; and (iv) soft-rock areas, viz., Gondwana and tertiary areas. North Bihar is generally rich in groundwater resources and three major saturated groundwater zones were identified based on the drilled depths of 690 meters below ground level (mbgl): The deep aquifer (300 to 440 mbgl), intermediate aquifer (50 to 200 mbgl) and upper shallow aquifer (20 to 70 mbgl). The deep aquifer is formed by the lower granular zone. Granular zones occurring within the middle clay zones form intermediate aquifer whereas the upper shallow aquifer is composed of the granular zone (Rao and Prasad 1994).

In the phreatic zone in Bihar, groundwater is developed through dug wells and shallow tube wells (CGWB 2006). The yield of these wells generally ranges from 1 to 3 liters per second (lps) (CGWB 2006). Wells tapping in the deeper aquifers in alluvial areas yield 3,070 lps while it is 3-15 lps in the consolidated formation. The main alluvial tract covers the entire North Bihar and these alluvial formations constitute prolific aquifers. In these aquifers, the yield of tube wells generally varies from 120 to 247 m^3/hr. However, the efficiency of these aquifers decreases in the South in the marginal tract. Auto-flow conditions (Artesian wells) are observed in the sub-Terai region of Madhubani, Sitamarhi and West Champaran districts. In South Bihar, boreholes located near lineaments/fractures in the hard-rock terrain can yield between 10 and 50 m^3/hr. The Bhabar belt is an exposed area of the confined aquifers of the North Bihar Plains. This is composed of medium- to fine-grained sand which becomes boulder towards the North. The groundwater table lies between 10 and 20 mbgl (Jain et al. 2009). Tables 3 and 4 show the aquifer properties of each district in North and South Bihar, respectively. In North Bihar, the water level fluctuation is between 1.57 and 9 mbgl during the pre-monsoon season, and from 0.25 to 8.35 mbgl during the post-monsoon season. A large fluctuation (pre-monsoon 1.57 to 7.64 and post-monsoon 0.25 to 8.35 mbgl) in water levels is observed in Saran District. The yield of this aquifer varies from 9.60 m^3/hr to 194.4 m^3/hr. Highest yield is recorded in the northwestern district (Siwan). Transmissivity generally ranges from 215 m^2/d to 5,163 m^2/d and the lowest value (29 m^2/d) is recorded in Saran district. In contrast, aquifers in Siwan and Vaishali districts show maximum transmissivity of 3,800 m^2/d and 5,163 m^2/d, respectively, compared to other districts in North Bihar. The lowest and highest storativity is recorded at Vaishali (0.13×10^{-7}) and Muzaffarpur districts (2.60×10^{-3}), respectively. Table 4 shows that the water level fluctuation in South Bihar ranges from 0.6 to 10 mbgl, and the maximum drop is recorded during the pre-monsoon period (10 mbgl). Aquifer properties generally vary with water-bearing formations. In South Bihar, wells in alluvium and quaternary alluvium formations provide maximum discharge compared to hard-rock formations. Wells in Patna, Buxer and Bhojpur districts give maximum yield (150 to 535 m^3/hr) and have high transmissivity (3,786 to 19,540 m^2/day) (Table 4).

According to CGWB (2011), annual replenishable groundwater resources of Bihar has been estimated at 28.63 Bm^3 and net groundwater availability is 26.21 Bm^3 (CGWB 2011; Ministry of Water Resources 2009). The annual groundwater draft for all uses is 11.35 Bm^3 and the average stage of groundwater development of Bihar is 43%. Table 5 provides details of the district-wise groundwater resources in Bihar estimated by CGWB using standard protocol (Ministry of Water Resources 2009). In Bihar, major irrigation practices rely on the network of canal systems whereas minor irrigation is managed by river lift irrigation, deep tube wells, shallow tube wells, dug wells, tanks and bamboo boring schemes. More than 80% of the land in this state is cultivable and 80% of the population depends on agricultural activities for their livelihoods. According to MoEF (2007), surface water irrigation contributed to 2.6 Mha and groundwater irrigation contributed to 0.96 Mha in Bihar until 1991. The canals and tube wells contribute 38% and 31%, respectively, in the overall irrigation water usage. The dug wells, rivers, lift irrigation and other sources have contributed 3.2%, 3.5%, 2.5% and 20.9%, respectively (MoEF 2007).

TABLE 3. Aquifer properties in North Bihar.

District	Average annual rainfall	Groundwater-bearing formation (mm)	Water level fluctuation (2006) (mbgl)		Discharge (m^3/hr)	Storativity (s)	Transmissivity (m^2/day)	Specific capacity (m^3/hr/m)
			Pre-monsoon	Post-monsoon				
Araria	NA	Recent Alluvium	2-6	1-3	NA	NA	NA	NA
Madhubani	1,289	Quaternary Alluvium	3-7.60	< 1-4.10	9.60-18 (auto-flow discharge)	1.00×10^{-3} - 1.80×10^{-4}	215-1,736	NA
Muzaffarpur	1,280	Alluvium	3.55-7.32	1.01-4.90	50.40-93.60	2.60×10^{-3}	1,274-1,576	NA
Gopalganj	1,170	Alluvium	1.66-4.67	1.24-3.35	72-180	2.30×10^{-3} - 4.30×10^{-4}	1,284-2,392	4.45-36.64
Siwan	1,029	Alluvium	3.09-6.27	2.15-4.80	158.40-194.40	1.10×10^{-3} - 3.30×10^{-4}	2,000-3,800	16.38-22.66
Saran	1,075	Quaternary Alluvium	1.57-7.64	0.25-8.35	NA	0.65×10^{-4}	29-1,776	NA
Vaishali	1,168	Alluvium	3-9	2-5	100	0.13×10^{-7}	621-5,163	NA
Darbhanga	1,142	Alluvium	3.31-6	1.75-4.10	NA	NA	NA	37-73
Katihar	2,194	Quaternary Alluvium	2.87-6.82	1.15-3.40	100	NA	NA	NA

Source: Compiled from GWIB-CGWB 2007.
Note: NA - Not available.

TABLE 4. Aquifer properties in South Bihar.

District	Average annual rainfall (mm)	Groundwater-bearing formation	Water level fluctuation (2006) (mbgl)		Discharge (m^3/hr)	Storativity (s)	Transmissivity (m^2/day)	Specific capacity (m^3/hr/m)
			Pre-monsoon	Post-monsoon				
Patna	1,076	Alluvium	3-8.6	1.4-7.3	176-535	1×10^{-4}	3,786-19,540	NA
Buxar	1,021	Quaternary Alluvium	3.6-9	1.6-6	180-200	1.1×10^{-3} - 3×10^{-4}	9,690-10,980	NA
Bhojpur	1,080	Alluvium	4-8	2-7	150-200	0.07×10^{-4}	4,769-15,886	NA
Munger	1,231	a) HR/FF of Quartzite and Phyllite b) US of Alluvium Plain	3-8	2-5	R.Allu: 10-150 O.Allu: 10-100	3×10^{-5} - 5×10^{-3}	10-500	NA
Bhagalpur	1,149	Alluvium	3.5-9.7	1.4-3.4	STW: 20-50	NA	100-600	NA
Sheikhpura	1,042	a) US of Alluvium Plain b) HR/FF Quartzite	6-10	1-7	NA	3×10^{-5} - 5×10^{-3}	5.25-2,250	NA
Lakhisarai	1,170	a) HR/FF of Quartzite, Phyllite and Granite b) US of Alluvium Plain	6.9-8.7	2.3-7	R.Allu: 10-150 O.Allu: 10-100 Pedi: 1-10	2.1×10^{-4}	1,238	NA
Banka	1,168	Quaternary Alluvium	3.2	5.1	60-107	2.8×10^{-4} - 4.8×10^{-3}	63-1,265	NA
Nawada	1,037	Quaternary Alluvium	2.2-8.8	0.6-6.6	28.8-216 (Allu) 36 (HR)	2.6×10^{-4} - 6.1×10^{-5}	361-1,717	NA

Source: Compiled from GWIB-CGWB 2007.

Notes: HR - Hard rock, FF - Fissured formation, Allu - Alluvium, O.Allu - Old alluvium, R.Allu - River alluvium, Pedi - Pediplain, US - Unconsolidated sediment, STW - Shallow tube well, NA - Not available.

TABLE 5. Dynamic groundwater resources and issues in North and South Bihar.

District	Net annual replenishable groundwater resources (2004) (Mm^3)	Annual groundwater draft (Mm^3)	Allocation of groundwater for domestic and industrial use (for 25-year calculation) (Mm^3)	Groundwater issues
North Bihar				
Araria	883.40	239.03	54.78	Waterlogging in command area
Madhubani	1,028.56	314.55	87.82	No issues
Muzaffarpur	1,097.68	522.22	NA	No issues
Gopalganj	633.61	316.73	NA	No issues
Siwan	827.87	455.43	NA	No issues
Saran	853.00	426.53	84.41	Flood, waterlogging, soil salinity, As contamination
Vaishali	740.09	381.18	68.73	Flood, waterlogging, As contamination in Bidupur
Darbhanga	552.15	246.16	80.51	No issues
Katihar	102.73	96.73	39.72	As contamination
South Bihar				
Patna	1,134.56	551.39	106.05	Flood
Buxar	618.50	180.87	38.04	As contamination in four blocks, F and Fe contamination
Bhojpur	705.00	247.87	437.09	As contamination in shallow aquifer. Contamination blocks are adjoining riverbed
Munger	26.45	7.89	2.63	Waterlogging, flood and river erosion - Diara area. F contamination in Khaira and Bhalwa Koul
Bhagalpur	669.94	196.40	451.19	Few patches have been identified as being contaminated with As
Sheikhpura	16.30	7.84	1.64	Water scarcity and poor yield
Lakhisarai	22.51	7.46	2.11	F contamination
Banka	414.53	135.58	38.49	Waterlogging and flood
Nawada	531.96	244.33	NA	F contamination in a few blocks

Source: Compiled from GWIB-CGWB 2007.
Notes: As - Arsenic, F - Fluoride, Fe - Iron, Mm^3 - million cubic meters, NA - Not available.

Jharkhand

In Jharkhand, groundwater mainly occurs in the unconfined aquifer formed by weathered residuum. Semi-confined and confined conditions exist in deeper fractures and joints. Groundwater-bearing formations in the northeastern part of the state are Chotanagpur granites and Rajmahal trap whereas granitic gneiss, quartzite and sandstone are major groundwater-bearing formations in the northwestern side of the state (Table 6). CGWB (2008) carried out groundwater exploration studies in Jharkhand and identified four potential fractured zones at variable depth within 200 mbgl.

Groundwater investigations were carried out by CGWB (GWIB-CGWB 2007) in 12 out of 24 districts, mostly in the northern part of Jharkhand (Table 6). The yield of the exploratory wells is from 0.25 to 151 m^3/hr and highly variable. Detailed aquifer parameters are given in Table 6. According to CGWB (GWIB-CGWB 2007) data, seasonal water table fluctuation generally occurs from 0.3 to 16.7 mbgl in Jharkhand (Table 6). Fluctuation ranges from 2.11 to 16.7 mbgl in the pre-monsoon season, and from 0.3 to 14 mbgl in the post-monsoon season. In Koderma District, a large fluctuation is observed in the water table (pre-monsoon - 3.9-16.7 mbgl; post-monsoon - 1.3-14 mbgl). In contrast, a small fluctuation is observed in the water table in Garhwa District (less than 2 m). Transmissivity data are not available for all districts. However, available data indicate that maximum transmissivity is recorded in Godda District (177 m^2/day). Likewise, the storativity values for aquifers are reported only for the eastern districts (Table 6). Unfortunately, except for the data obtained from CGWB, there is no detailed data available about aquifer properties of Jharkhand. The Water Resources Department (Government of Jharkhand) has been working on groundwater development and estimation of potential. However, they do not have detailed data on aquifer parameters.

Total water availability in this state is 32.779 Bm^3 (Water Resources Department, Government of Jharkhand 2011). In this estimation, surface water and groundwater contribute 27.528 Bm^3 and 5.251 Bm^3, respectively. Table 7 provides details of groundwater resources in Jharkhand. In the cultivable land (3.8 Mha), 80% of the area is drought-prone and 7% is flood-prone. According to CGWB (2011), annual replenishable groundwater resources in Jharkhand is 5.96 Bm^3, estimated by standard protocol (Ministry of Water Resources 2009). The net annual groundwater availability and groundwater draft are 5.41 Bm^3 and 1.61 Bm^3, respectively. The stage of groundwater development is 30%. According to Water Resources Department, Government of Jharkhand (2009), annual replenishable groundwater, net groundwater availability, annual groundwater draft and stage of groundwater development in Jharkhand are 5.96 Bm^3, 5.41 Bm^3, 1.61 Bm^3 and 30%, respectively. In this state, agricultural activities depend on both groundwater and surface water resources. According to Water Resources Department, Government of Jharkhand (2011), irrigation activities consume 59% of total groundwater usage and the remaining is obtained from surface water (41%). Likewise, water consumption in the municipal sector is also balanced by groundwater (10.60%) and surface water (6%).

TABLE 6. Aquifer properties in Jharkhand.

District	Average annual rainfall (mm)	Groundwater-bearing formation	Water level fluctuation (2006) (mbgl)		Discharge (m^3/hr)	Storativity (s)	Transmissivity (m^2/day)
			Pre-monsoon	Post-monsoon			
Ranchi	1,316	Granite, Quartzite, Alluvium	2.11-11	1.63-5.60	2-23	NA	NA
Garhwa	1,193	CGG and SS	7-8.78	4.93-6.71	8-20	1.7×10^{-4}	7.16
Palamu	1,163	CGG, Vindhyan Limestone, Shale, Recent Alluvium, Gondwana SS and Shale	5.10-12.90	2.60-9.24	5-62	NA	NA
Hazaribagh	1,234	Granites, Granite gneiss, Gondwanas	4.10-10.10	2.50-5.80	0.30-65	NA	NA
Koderma	1,192	Granite gneiss, Granite	3.90-16.70	1.30-14	1.50-12.30	NA	13-29
Bokaro	1,198	Granite gneiss, Quartzite	6.80-11.30	4.10-8.80	< 3.60-7.56	NA	
Dhanbad	1,241	Granite gneiss, Sandstone	2.86-14.60	1.37-4.60	1-12	NA	0.80-105
Jamtara	1,294	Precambrian Chotanagpur	5.45-9.43	2.41-3.80	0.90-26	NA	NA
Deoghar	1,162	Chotanagpur Granite	6.37-10.40	2.55-5.47	0.60-151	2.2×10^{-4} - 1.0×10^{-5}	22-128
Pakur	1,399	Rajmahal Trap	3.06-9.72	0.30-5.83	9-51	1.3×10^{-2} - 7.3×10^{-2}	29-176
Godda	1,063	Chotanagpur Granite	4.70-11.64	2.50-5.80	0.25-49.20	4.3×10^{-3} - 1.01×10^{-5}	8-177
Sahibganj	1,575	NA	3.45-14.90	0.86-7.67	6.12-51.60	1.4×10^{-4} - 7.3×10^{-5}	32.30-176

Source: Compiled from GWIB-CGWB 2007.
Notes: CGG - Chotanagpur Granite Gneiss, SS - Sandstone, NA - Not available.

TABLE 7. Dynamic groundwater resources and issues in Jharkhand.

District	Net annual replenishable groundwater resources (2004) (Mm^3)	Annual groundwater draft (Mm^3)	Allocation of groundwater for domestic and industrial use (for 25-year calculation) (Mm^3)	Groundwater issues
Ranchi	516.98	125.64	61.22	Declining groundwater level and F contamination
Garhwa	274.11	72.64	25.10	F contamination
Palamu	341.03	82.31	36.19	F and NO_3 contamination
Hazaribagh	374.13	100.33	47.45	Low discharge of bore wells in Gondwana formations
Koderma	88.09	22.57	12.79	F contamination in Koderma and Satgawan block
Bokaro	220.82	38.56	30.81	High F, Fe, Mn and Zn contamination around the industrial area
Dhanbad	227.00	52.18	59.43	NO_3 and F contamination
Jamtara	144.01	21.40	12.92	No issues
Deoghar	161.03	35.46	25.96	Fe contamination
Pakur	142.36	17.31	15.82	F contamination
Godda	141.92	54.18	22.81	F and NO_3 contamination
Sahibganj	166.45	50.58	20.81	As contamination

Source: Compiled from GWIB-CGWB 2007.
Notes: F - Fluoride, As - Arsenic, NO_3 - Nitrate, Fe - Iron, Mn - Manganese, Zn - Zinc.

West Bengal

In West Bengal, groundwater occurs in confined, semi-confined and unconfined conditions. The aquifer along the entire coast is under confined conditions. Two-thirds of West Bengal is occupied by unconsolidated quaternary sediments, and the groundwater occurrence and movement are regulated by primary porosities in the sediments. Secondary porosity is formed by the weathering of hard rock which acts as a repository for groundwater. These waters are under unconfined conditions. Fractures, joints and other fissures developed in Archaean to Proterozoic gneisses and schists, Gondwana super group of rock and Siwalik rocks, and Rajmahal basaltic traps form the secondary openings. Groundwater moves down the gradient through these formations and mostly occurs under confined conditions. Alluvial formation with a thick granular zone in the extreme northern part of West Bengal is a recharge zone for the unconfined aquifers with high permeability, which receives an average annual rainfall of 3,000 mm. The granular zone is separated from the confined aquifer by clay layers. A thick granular zone (150-250 m) existed in Murshidabad and Nadia districts and acts as a recharge zone for confined or deeper aquifers down South. The clay layer appears in the southern part (as in the northern part) and the thickness increases from 2 to 30 m towards the South. In the southern part, in general, an alternative sequence of sand and clay layers occur towards a depth of about 300 m. In West Bengal, three aquifers were identified: (i) depth is within 100 mbgl, (ii) depth is 120 to 160 mbgl, and (iii) depth is 200 to 250 mbgl.

In West Bengal, generally, wells in hard-rock terrain show poor yield, transmissivity and storativity compared to sedimentary formations. Tables 8 and 9 show the aquifer properties based on districts in West Bengal. According to Ray and Shekhar (2009), the discharge of wells in consolidated formations varies from 5 to 50 m^3/hr. The transmissivity is less than 50 m^2/day in Rajmahal trap and consolidated rock formations. In contrast, there is excellent groundwater potential in sedimentary formations, older alluvium and recent alluvium in unconsolidated formations. In these formations, the aquifer is under both unconfined and confined conditions. Wells existing in these formations discharge more than 200 m^3/hr and the maximum discharge (612 m^3/hr) has been recorded in Cooch Behar District (GWIB-CGWB 2007). Wells existing in the southeastern part of West Bengal (South 24 Parganas, North 24 Parganas, Haora and Nadia districts) show excellent yield (~ 200 m^3/hr). Transmissivity of this aquifer varies from 397 to 8,607 m^2/day and storativity from 1.87×10^{-5} to 3.3×10^{-2}. Maximum transmissivity is noted in Nadia District (8,607 m^2/day). In West Bengal, the water level fluctuation during the pre-monsoon season varies from 0.35 mbgl to 19.95 mbgl whereas during the post-monsoon season it varies from 0.22 mbgl to 31 mbgl. Groundwater level in Kolkata is below 10 mbgl during the post-monsoon season and it reaches about 20 mbgl during the pre-monsoon season. According to CGWB (2011), total groundwater recharge is 30.50 Bm^3 and net groundwater availability is 27.58 Bm^3.

In West Bengal, 51.02 Bm^3 of water is generated annually from rainfall and 21% of average annual rainfall is estimated to recharge the aquifer (WBPCB 2009). In this state, 60% of the water resources is available in North Bengal and the remainder in South Bengal. According to MoEF (2010), replenishable groundwater resources including natural discharge is 34.20 Bm^3, of which 69% is in South Bengal and the remainder in North Bengal. West Bengal receives 598.56 Bm^3 of transboundary water from neighboring states. In addition, Ganga carries 525 Bm^3 of water from its large catchment. CGWB (2011) reported that the annual replenishable groundwater resources is 30.50 Bm^3 and natural recharge is 2.92 Bm^3 based on a survey carried out in 2009. Net annual groundwater availability and groundwater draft are 27.58 Bm^3 and 10.90 Bm^3, respectively. Current annual groundwater draft for irrigation and domestic/industrial uses are 10.11 and 0.79 Bm^3, respectively (CGWB 2011; Ministry of Water Resources 2009). Net groundwater availability for future irrigation is 15.32 Bm^3 and the stage of groundwater development is 40%. Table 10 shows the district-wise dynamic groundwater resources in West Bengal. The availability of groundwater and surface water resources in West Bengal varies across space and time. According to MoEF (2010), 28% of the groundwater and 60% of the surface water are available in North Bengal, which supports only 18% of the population of the region. However, 82% of the population living in South Bengal access only 40% of the surface water and consume 78% of groundwater for their requirements. WBPCB (2009) and MoEF (2010) reported that the overall available surface water and groundwater resources in West Bengal are 51.01 Bm^3 and 34.21 Bm^3, respectively. Per capita water availability varies from one district to another (WBPCB 2009; MoEF 2010). Nadia, Haora, Hooghly, Kolkata and North 24 Parganas districts face severe water scarcity (less than 500 m^3/capita). The Irrigation and Waterways Department (IWD) in West Bengal reported that available surface water and groundwater resources are 132.9 Bm^3 and 14.6 Bm^3, respectively. Groundwater is completely utilizable whereas only 53.1 Bm^3 of the surface water is usable. MoEF (2010) reported that 91.4% of rural households and 41.2% of urban households depend on groundwater in West Bengal. More than 70% of the population of the state relies directly or indirectly on agriculture for their livelihoods. Irrigation depends mainly on water from canals and shallow tube wells (STW). In this state, around 75% of the total area (3,591,305 ha) is irrigated with water from canals (24%) and STW (50%). Surface flow (8%), surface lift (12%) and deep tube wells (5%) are also employed for irrigation (Ray and Shekhar 2009).

TABLE 8. Aquifer properties in West Bengal (South).

District	Average annual rainfall (mm)	Groundwater-bearing formation	Water level fluctuation (2006) (mbgl)		Discharge (m^3/hr)	Storativity (s)	Transmissivity (m^2/day)
			Pre-monsoon	Post-monsoon			
South 24 Parganas	1,800	Quaternary and tertiary alluvium	DW: 0.35-5.56 TW: 2.50-6.80	DW: 0.30-1.35 TW: 2.58-6.48	11.95-221.69	2×10^{-4} - 3.3×10^{-2}	397-6,514
North 24 Parganas	1,525	Sand, silt and gravel	2.00-13.60	1.64-10.66	56.16-249.88	1.05×10^{-3} - 1.45×10^{-4}	699-8,127
Purba (East) Medinipur	1,640	Quaternary alluvium and tertiary sedimentary	3.05-16.34	2.71-11.63	3.60-86.4	1.30×10^{-4} - 9×10^{-4}	434-4,000
Paschim (West) Medinipur	1,542	Quaternary alluvium, tertiary sedimentary, and weathered and fractured hard rock	1.18-17.70	1.28-11.18	3.60-72	1.10×10^{-2} - 3.87×10^{-5}	43-4,106
Haora	1,536	Quaternary alluvium	DW: 1.06-4.06 TW: 5.29-11.13	DW: 1.02-2.20 TW: 5.01-9.99	36-211.64	45×10^{-4}	446-2,515
Kolkata	1,647	Quaternary alluvium	12.09-19.59	10.72-15.42	25.99-70.60	33×10^{-3} - 20×10^{-3}	2,065-2,276
Hooghly	1,477	Alluvial sediments	0.40-18.69	0.39-14.75	39-50.45	4.14×10^{-1} - 1.87×10^{-5}	1,860-4,128
Bankura	1,211	Weathered materials with 15 m and fracture in GG (30-60 mbgl). In alluvium - both old and recent (30-270 mbgl)	5-10, maximum: 13.28	2-5, maximum: 12.31	8.28-123.98	1.02×10^{-3} - 2.18×10^{-4}	272.90-806.40
Purulia	1,322	Weathered mantle, saprolitic zone, fractured zone of hard rock, unconsolidated sedimentary	4.32-11.68	2.07-5.60	1.19-6.64		
Bardhaman	1,442	Quaternaries and tertiaries	DW: 0.74-19.95 TW: 2.95-19.03	DW: 0.22-11.63 TW: 1.03-31	0.61-35.74	3×10^{-4} - 188×10^{-4}	30.77-1,700
Nadia	1,474	Quaternary alluvium	DW: 4.42-7.92 PZ: 3.41-8.12	DW: 2.42-5.97 PZ: 1.04-7.32	3.60-221.40	0.74×10^{-3} - 6.20×10^{-3}	1,487-8,607
Birbhum	1,601	Weathered mantle and fractures in Archaean granites, Gondwana and Rajmahal trap, alluvium	5-10, Maximum: 16.35	Up to 5, maximum: 14.75	HR: 2.99-19.01 Allu: 2.88-162.83	Allu: 0.20×10^{-3} - 4.60×10^{-4}	Allu: 700-2,900
Murshidabad	1,417	Quaternary alluvium	DW: 1.14-10.55 PZ: 4.30-19.90	DW: 0.56-7.65 PZ: 0.35-14.02	3.60-86.40	7.60×10^{-4} - 4.98×10^{-4}	2,500-8,000

Source: Compiled from GWIB-CGWB 2007

Notes: DW - Dug well, TW - Tube well, PZ - Piezometer well, Allu - Alluvium, HR - Hard rock, GG – Granite Gneiss.

TABLE 9. Aquifer properties in West Bengal (North).

District	Average annual rainfall (mm)	Groundwater-bearing formation	Water level fluctuation (2006) (mbgl)		Discharge (m^3/hr)	Storativity (s)	Transmissivity (m^2/day)
			Pre-monsoon	Post-monsoon			
Maldah	1,919	Quaternary alluvium	3.70-12.22	1.64-6.16	30-150	1.16×10^{-4} - 4.98×10^{-4}	3,000-7,000
Dakshin Dinajpur	1,705	Recent alluvium consists of sand and gravel	1.14-12.29	1.59-6.65	38.16	NA	500-1,500
Uttar Dinajpur	2,042	Recent alluvium consists of sand and gravel	2.47-5.64	0.53-5.39	25.20-288	NA	400-2,000
Darjeeling	2,841	Consolidated formation of Dalings and Darjeeling Gneiss, Piedmont zone, unconsolidated sediments	1.10-9.69	1.29-4.66	5.40-120.49	NA	20-2,500
Cooch Behar	3,067	Quaternary alluvium	1.20-6.55	0.56-7.05	288-612	NA	NA

Source: Compiled from GWIB-CGWB 2007.

TABLE 10. Dynamic groundwater resources and issues in West Bengal.

District	Net annual replenishable groundwater resources (2004) (Mm^3)	Annual groundwater draft (Mm^3)	Allocation of groundwater for domestic and industrial use (for 25-year calculation) (Mm^3)	Groundwater issues
South 24 Parganas	68	135.77	NA	As and Fe contamination, salinity hazards and declining groundwater level
North 24 Parganas	1,419	1,000	108.59	As, Fe and Cl contamination
Purba (East) Medinipur	743.40	288.82	39.65	Salinity in coastal tract, Fe contamination and declining groundwater level
Paschim (West) Medinipur	3,445	1,239	NA	Groundwater scarcity in hard-rock formations, Fe contamination and declining groundwater level
Haora	333.30	68.70	24.21	Salinity, and Fe and As contamination
Kolkata	74.46	111.40	116.96	Declining groundwater level, seawater intrusion and As contamination
Hooghly	1,526	590.93	84.19	Fe and As contamination (in one block)
Bankura	1,899	568.37	63.76	Groundwater scarcity in hard-rock formations and drought-prone areas, high levels of F contamination
Purulia	701.47	96.66	49.40	High levels of F contamination
Bardhaman	3,033	1,319	121.87	As and Fe contamination, and mining and industrialization affect water quality and quantity
Nadia	2,172	1,653	126.41	As and Fe contamination
Birbhum	1,526	393.59	64.73	F contamination and groundwater scarcity in hard-rock formations
Murshidabad	22.70	20.08	183.03	As and Fe contamination
Maldah	1,271.28	723.79	82.78	As contamination and waterlogging
Dakshin Dinajpur	871.20	412.31	35.19	F contamination
Uttar Dinajpur	1,537	722.65	58.08	F contamination
Darjeeling	469.57	25.07	17.19	High runoff
Cooch Behar	2,085	347.82	50.06	High levels of Fe contamination

Source: Compiled from GWIB-CGWB 2007.
Notes: NA - Not available, As - Arsenic, Fe - Iron, F - Fluoride, Cl - Chloride.

Table 11 shows the comparative analysis of groundwater resources, availability, utilization and stage of development in the Indian part of the Eastern Ganges Basin. According to CGWB (2011), the stage of groundwater development of Bihar, Jharkhand and West Bengal does not exceed 50%, which highlights the existence of enormous untapped groundwater potential in the EGB. Further, groundwater usage for irrigation is 21.07 Bm^3, which is 35.59% of total net groundwater availability in the Indian part of the EGB. Hence, neither annual replenishable groundwater resources nor net groundwater availability is completely utilized, and some potential exists for groundwater development to support intensive irrigation in this region.

TABLE 11. Estimated dynamic groundwater resources availability, utilization and stage of development in the Indian part of the Eastern Ganges Basin.

State	Annual replenishable groundwater resources (Bm^3)	Natural recharge (Bm^3)	Net groundwater availability (Bm^3)	Annual groundwater draft (Bm^3)			Stage of groundwater development (%)
				Irrigation	Domestic, industrial and other uses	Total	
Bihar	28.63	2.42	26.21	9.79	1.56	11.35	43
Jharkhand	5.96	0.55	5.41	1.17	0.44	1.61	30
West Bengal	30.50	2.92	27.58	10.11	0.79	10.90	40
Total	*65.09*	*5.89*	*59.2*	*21.07*	*2.79*	*23.86*	*40*

Source: Compiled from CGWB 2011.

Groundwater Quality

Bihar

In Bihar, groundwater quality is generally suitable for irrigation. Except for a few places, groundwater quality is also suitable for domestic purposes. Groundwater contamination is an issue in Bihar as it is the only source of water for drinking purposes and domestic uses. Table 12 provides details of groundwater quality issues and the districts affected in Bihar, Jharkhand and West Bengal (GWIB-CGWB 2007). The contaminants may be classified by its origin: geogenic and anthropogenic. Geogenic contaminants are originated by geological formations such as arsenic, fluoride and iron. Nitrate is a good indicator of anthropogenic contamination. In Saran District, the shallow aquifer (50 m depth) contains arsenic, especially in Sonepur, Dighwara, Chapra Sadar and Revelganj villages. In Munger District, fluoride contamination of groundwater has been found in Khaira and Bhalwa Koul villages.

Jharkhand

In Jharkhand, groundwater quality is mostly suitable for irrigation. Identifying the location for bore well or dug well installation is a complicated issue due to hard-rock formation. Further, declining groundwater levels, water scarcity and the drying of dug wells during the summer are predominant problems in this state. Since groundwater quality is a concern, fluoride and iron contaminations are a common problem throughout the state (Table 12). The Nitrate concentration in groundwater exceeds World Health Organization (WHO) and Bureau of Indian Standards (BIS) in Palamu, Dhanbad and Godda districts, which highlights the role of surface contamination. In Sahibganj District, arsenic contamination was also identified in the groundwater in the Sahibganj block (Hazipur Bihta, Dihari, Bari Kudarjana, Nadhi Dera, Reza Nagar, Baluadiara and Chanan villages) (GWIB-CGWB 2007).

West Bengal

In West Bengal, the groundwater is generally neutral to slightly alkaline in nature. The electrical conductivity (EC) of water varies between 500 to 2,000 µS/cm at 25 °C. Deeper aquifer in the southern coastal tract shows slightly high EC (1,000 to 2,000 µS/cm). The upper aquifer also shows very high EC, especially in the southeast (20,000 µS/cm). Water scarcity and depletion of groundwater levels become common issues in West Bengal. Water scarcity is a real issue in the western and northern parts (hilly tracts) of the state. Districts of Purulia, western part of Bankura, Birbhum, Bardhaman and Paschim Medinipur experience this problem (Table 12). Depletion of water level is identified in central Kolkata. In the last 40 years, the groundwater level has dropped almost 5 to 9 m. Table 12 illustrates the groundwater quality issues and the areas affected. The most common groundwater contaminants are arsenic, iron, fluoride, nitrate, chloride and salinity. Heavy pumping causes lowering of the groundwater level followed by saline water intrusion in the coastal areas. Among the contaminants, arsenic gets higher prominence because 16.7 million people are affected by arsenic contamination (Planning Commission, Government of India 2010).

TABLE 12. Groundwater quality problems in Bihar, Jharkhand and West Bengal.

Contaminants	Range	Bihar Districts affected (in part)	Jharkhand Districts affected (in part)	West Bengal Districts affected (in part)
Arsenic	> 0.05 mg/l	Begusarai, Bhagalpur, Bhojpur, Buxar, Darbhanga, Katihar, Khagaria, Kishanganj, Lakhisarai, Munger, Patna, Purnea, Samastipur, Saran, Vaishali	Sahibganj	Bardhaman, Hooghly, Haora, Maldah, Murshidabad, Nadia, North 24 Parganas, South 24 Parganas
Chloride	> 1,000 mg/l	-	-	South 24 Parganas, Haora
Fluoride	> 1.5 mg/l	Aurangabad, Banka, Buxar, Bhabua (Kaimur), Jamui, Munger, Nawada, Rohtas, Supaul	Bokaro, Giridih, Godda, Gumla, Palamu, Ranchi	Bankura, Bardhaman, Birbhum, Dakshin Dinajpur, Malda, Nadia, Purulia, Uttardinajpur
Iron	> 1.0 mg/l	Aurangabad, Begusarai, Bhojpur, Buxar, Bhabua (Kaimur), East Champaran, Gopalganj, Katihar, Khagaria, Kishanganj, Lakhisarai, Madhepura, Muzaffarpur, Nawada, Rohtas, Saharsa, Samastipur, Siwan, Supaul, West Champaran	Chatra, Deoghar, East Singhbhum, Giridih, Ranchi, West Singhbhum	Bankura, Bardhaman, Birbhum, Dakshin Dinajpur, East Medinipur, Haora, Hooghly, Jalpaiguri, Kolkata, Murshidabad, North 24 Parganas, Nadia, South 24 Parganas, Uttar Dinajpur, West Medinipur
Nitrate	> 45 mg/l	Aurangabad, Banka, Bhagalpur, Bhojpur, Bhabua, Patna, Rohtas, Saran, Siwan	Chatra, Garhwa, Godda, Gumla, Lohardaga, Pakur, Palamu, Paschimi Singhbhum, Purbi Singhbhum, Ranchi, Sahibganj	Bankura, Bardhaman
Salinity	EC > 3,000 µS/cm	-	-	Haora, Medinipur, South 24 Parganas

Sources: GWIB-CGWB 2007; CGWB 2011.

Bangladesh

General

Bangladesh constitutes a part of the Ganges Basin, and lies at the head of the Bay of Bengal. The basin is about 200 km wide in the northeast and broadens to about 500 km in the vicinity of the Bay of Bengal (Aggarwal et al. 2000). It has a short border with Myanmar in the southeast, a common border to the west, north and east with India, and is bounded by the Bay of Bengal in the South (FAO 2011). Around 80% of the landmass is covered by fertile alluvial lowland that comes under a part of the Greater Bengal Plain (Lower Gangetic Plain). The country is flat with some hills in the northeast and southeast; and a great plain lies almost at sea level along the southern part of the country and rises gradually towards the North. The land elevation on the plain varies from 0 to 90 m above mean sea level (amsl) and the maximum elevation is 1,230 m amsl at Keokradong in the Rangamati hill district. The geomorphology comprises almost 80% of floodplains with some terraces and hilly areas. About 7% of the total area of Bangladesh is covered with rivers and inland water bodies, and these areas are routinely flooded during the monsoon. Forest cover account for about 16% of the total area of the country (FAO 2011).

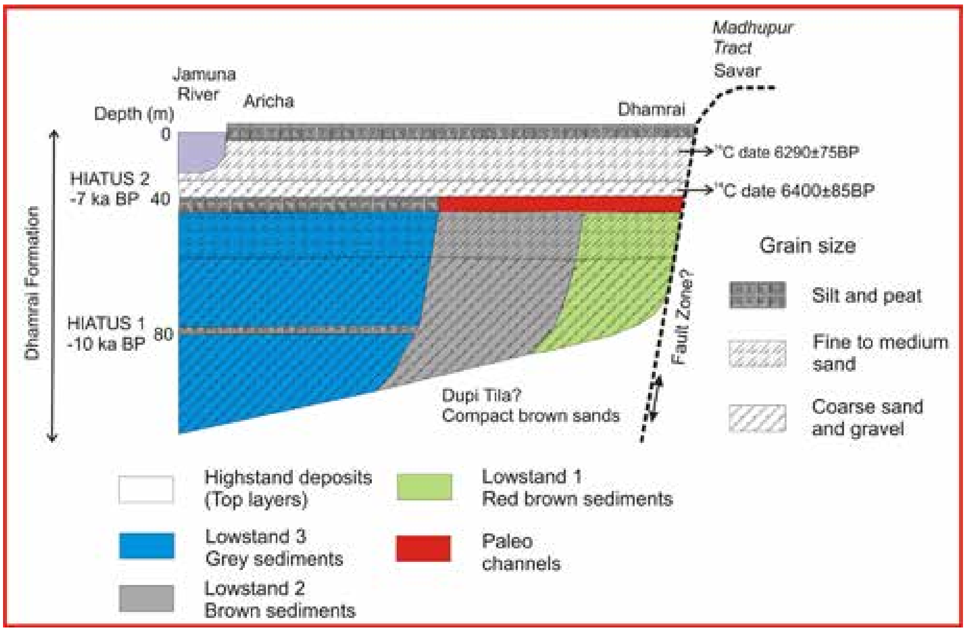
Bangladesh experiences a tropical monsoon climate with significant variations in rainfall and temperature throughout the country. Mean annual temperature is about 25 °C, with extreme low (4 °C) and high (43 °C) temperatures. During March and May, humidity and temperature increase. Humidity ranges between 60% in the dry season and 98% during the monsoon. Very hot and wet periods are observed from June to October. The average annual precipitation is 2,320 mm and it varies from 1,110 mm in the extreme northwest to 5,690 mm in the northeast. The country is regularly experiencing droughts, floods and cyclones. Bangladesh receives 85% of mean annual rainfall during the monsoon (May to September) (BGS and DPHE 2001). The country's mean annual lake evaporation is approximately 1,040 mm, which is about 45% of the mean annual rainfall (FAO 2011). Monthly evapotranspiration increases from 70 to 90 mm during January and 180 mm from March to May.

Geology and Lithology

The basin comprises geosynclinals deposits of the late Cretaceous age and a thick sequence of tertiary marine continental deposits. According to Zahid and Ahmed (2006), the surface of Bangladesh is classified by four major physiographic units: a) Tertiary sediments in the northern and eastern hills, b) Pleistocene terraces in the Madhupur and Barind tracts, c) Recent (Holocene) floodplains of the GBM River Basin, and d) Delta covering the remaining part of the country. Holocene floodplain deposits cover most of the surface area of present-day Bangladesh.

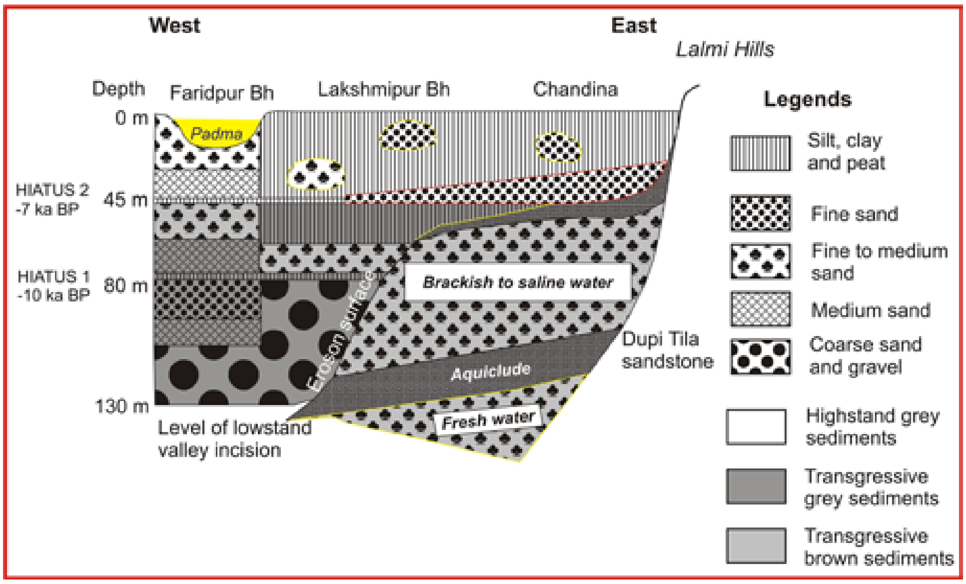
Alam et al. (1990) summarized the geological information of Bangladesh with the compilation of remotely sensed data, superficial deposits and data from oil-field explorations (BGS and DPHE 2001). A conceptual model of the Upper Pleistocene and Holocene sediments beneath the Brahmaputra fluvial floodplain west of Dhamrai was constructed by BGS and DPHE (2001) using the data obtained from Bangladesh Agricultural Development Corporation (BADC) for deep tube wells, and British Geological Survey (BGS) for test boreholes (Davies 1989), for Dhamrai, Singair, Manikganj, Saturia and Savar areas (Figure 2). BGS and DPHE (2001) also developed a conceptual model of the Upper Pleistocene and Holocene sediment distribution in the delta (Figure 3). It was created using lithological data from the Faridpur, Lakshmipur and Chandina areas related to sea-level change and regional tectonics.

FIGURE 2. Geological cross-section through the Late Quaternary fluvial sediments within the incised Jamuna channel, central GBM system.



Source: after BGS and DPHE 2001.

FIGURE 3. Hydrogeological cross-section of the southeast GBM delta, showing Late Quaternary sediments.



Source: after BGS and DPHE 2001.

Groundwater Potential and Challenges

In Bangladesh, the quaternary alluvium comprises a huge aquifer with reasonably good transmission and storage properties. The aquifer is recharged by heavy rainfall and inundation during the monsoon. Major aquifer systems belong to the Late Pleistocene Holocene sediments. In part of the southeast region, multilayered aquifer conditions exist. On a regional basis, UNDP (1982) described three-layer aquifers between Holocene and Plio-Pleistocene formations. These are the 1) Upper (shallower) or the composite aquifer, 2) Main aquifer, and 3) Deep aquifer (Zahid and Ahmed 2006; GWTF 2002).

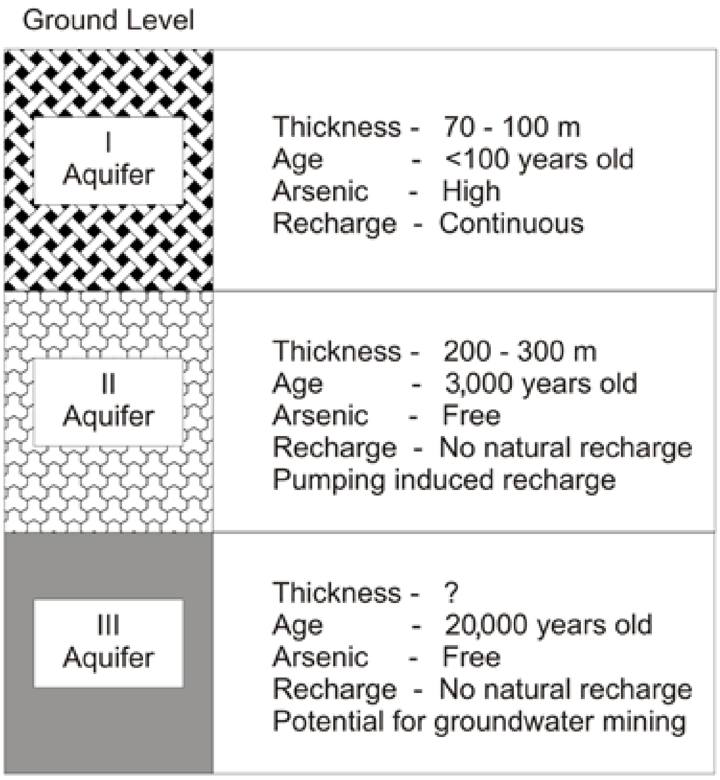
The upper (shallower) or the composite aquifer: Very fine to fine sand in places inter-bedded or mixed with medium sand of very thin layers are commonly identified below the upper clay and silt unit of a depth ranging from less than a few meters to several hundred meters. The sand layers are separated by a discontinuous thin clay layer. This aquifer represents the uppermost water-bearing zone.

The main aquifer: It occurs less than 5 m in the northwest to 75 m in the South and is a main water-bearing zone in Bangladesh. It is made up of medium- and coarse-grained sediments, inter-bedded with gravel in places, which occurs to depths of about 140 mbgl. Groundwater is tapped predominantly from this aquifer zone. This aquifer is either semi-confined or leaky or consists of stratified interconnected, unconfined water-bearing zones.

The deeper aquifer: It is isolated from the overlying main aquifer by one or more clay layers of varied thickness and extent. It comprises of medium to coarse sand, inter-bedded with fine sand in places, silt and clay. In this aquifer, large-scale extraction is not encouraged in the coastal region due to the possibility of seawater intrusion or leakage from the upper aquifer.

Barker and Herbert (1989) developed a three-layer model based on pumping test data, which is the commonly employed conceptual model used to explain recharge and abstraction in this aquifer. According to Barker and Herbert (1989), the first layer is formed by upper clay and sand (thickness 5-15 m) and the second layer is made up of silty to fine sand (thickness 1-60 m). The third layer, referred to as the lower shallow/main aquifer, is made up of medium- to coarse-grained sand and gravel (thickness 5-75 m) (BGS and DPHE 2001; UNDP 1982; Barker and Herbert 1989). Based on hydrogeological and isotope data, Aggarwal et al. (2000) suggested a revised model for the aquifer system in Bangladesh as shown in Figure 4.

FIGURE 4. Hydrogeological model based on isotope data.



Source: after Aggarwal et al. 2000.

Unfortunately, the three-layer aquifer model is not taking into account the sedimentological parameters or the depositional history of the aquifer sediments and the classification made by depth. However, the sedimentation rate and subsidence in the whole of the Bengal Basin were not uniform throughout the Quaternary. Hence, an attempt was made to divide the aquifer systems in the GBM Delta Complex from a geological point of view (i.e., Late Pleistocene-Holocene sediments) (GWTF 2002). In this classification, the major divisions are: 1) Plio-Pleistocene aquifers, and 2) Late Pleistocene-Holocene Aquifers. Again, the Late Pleistocene-Holocene Aquifers are classified into: a) Late Pleistocene-Early Holocene Aquifers, b) Middle Holocene Aquifers, and c) Upper Holocene Aquifers (GWTF 2002).

Plio-Pleistocene Aquifers: The Plio-Pleistocene Aquifers of the Dupi Tila Formation lies beneath the Pleistocene Madhupur clay formation. It is formed by light gray to yellowish brown, medium to coarse sand with pebble beds. It is confined to semi-confined in nature. Total water consumption of Dhaka city is withdrawn from this aquifer.

Late Pleistocene-Early Holocene Aquifers: This aquifer is not continuous all over the country and corresponds to the deep aquifer of the UNDP (1982) study, lower part of the deep aquifer of the BGS and DPHE (2001) study and the third aquifer of Aggarwal et al. (2000). The age of this aquifer is about 20,000 years old as assessed by isotopes data (Aggarwal et al. 2000). The sediments of this aquifer are, to some extent, related to the Late Pleistocene-Early Holocene Unit of the sediment section.

Middle Holocene Aquifers: This aquifer may be considered as being in a similar position in the geological section as the Main Aquifer (UNDP 1982), the Second Aquifer (Aggarwal et al. 2000) or the Lower Shallow Aquifer (BGS and DPHE 2001) in the floodplain and deltaic areas of Bangladesh. According to the dating report of Aggarwal et al. (2000), this aquifer is about 3,000 years old.

Upper Holocene Aquifers: It is developed all over the deltaic and floodplain areas, and does not occur in the Chandina Formation areas (Tippera Surface). In the lower part, it is made up of silt and clay at the bottom, and fine sand at the top. The upper part is comprised of silt and clay, and is commonly found to be inter-bedded or mixed with medium sand. This aquifer is in a similar position in the geological section as the Upper Composite Aquifer in UNDP (1982), Upper Shallow Aquifers in BGS and DPHE (2001) and First Aquifer in Aggarwal et al. (2000). The age of this aquifer is close to 100 years (Aggarwal et al. 2000).

The main aquifers in Bangladesh and their properties are given in Table 13. According to BGS and DPHE (2001), aquifer properties such as hydraulic conductivity and transmissivity are calculated using 500 pumping tests conducted by Pitman (1981) and UNDP (1982), 7,000 commissioning tests conducted by MMP (1977) and MMI (1992), and pumping tests and flow logging of 16 boreholes conducted by Davies et al. (1988). Table 14 reveals the groundwater resources and usage in Bangladesh. The internal renewable water resources are estimated as 105,000 Mm^3/year (Table 14). This includes 84,000 Mm^3 of surface water produced internally as stream flows from rainfall and about 21,000 Mm^3 of groundwater resources produced within the country. Part of the groundwater comes from the infiltration of surface water with an external origin. Since annual cross-border river flows and entering groundwater are estimated to be 1,121,600 Mm^3, the total renewable water resources are, therefore, estimated to be 1,226,600 Mm^3/year (FAO 2011). The utilization of groundwater and surface water in irrigation is illustrated in Table 14. In the overall water usage, groundwater contributes 79% of total agricultural water use. Groundwater pumping for irrigation lowers the groundwater table or drawdown. In urban areas, especially Dhaka City, the declining trend in groundwater is more than 1.0 m/year. In the last 32 years, the decline in groundwater levels is 20 to 30 m (Zahid and Ahmed 2006). BADC (2006) also reported that permanent depletion of groundwater levels were encountered in some locations, especially in the Dhaka metropolitan area. Average annual decline in groundwater levels is about 3 m in the Dhaka City as well as in the northwest region of the country (BADC 2006).

TABLE 13. Relationship between average aquifer test results and geological formation in Bangladesh.

Aquifer type/district or region	Transmissivity (m^2/d)	Storage coefficient	References
Deep Aquifer semi-confined by Upper Shallow Aquifer (Chandina Formation)			
Comilla District	1,200	1.3×10^{-3}	UNDP 1982
Noakhali District	617		MMI 1993
Sylhet Floodplains	460	5.6×10^{-4}	MMI 1992
Lower Shallow Aquifer (Dhamrai Formation)			
Dhaka (Dhamrai)	3,480	8.5×10^{-4}	Barker et al. 1989
Manikganj	4,211	3.9×10^{-4}	Barker et al. 1989
Tangail	2,803	2.9×10^{-3}	UNDP 1982
Upper Shallow Aquifer (Highstand Alluvium)			
Bogra District	2,380	1.1×10^{-3}	UNDP 1982
Dinajpur District	2,755	2.8×10^{-3}	UNDP 1982
Nawabganj	3,172	6.7×10^{-3}	Ahmed 1994
Pabna District	4,316		UNDP 1982
Rangpur	4,384	2.6×10^{-3}	UNDP 1982
Jessore District	3,660	1.9×10^{-3}	UNDP 1982
Kushtia District	3,780	2.0×10^{-3}	UNDP 1982
Deep Aquifer (Old Deep Aquifer Alluvium)			
Khulna District	3,100	1.0×10^{-3}	Rus 1985
Deep Aquifer (Dupi Tila Formation)			
Dhaka City	1,333	8.3×10^{-4}	EPC/MMP 1991
Madhupur Tract	1,161	1.7×10^{-3}	UNDP 1982; MMP/HTS 1982; MMI 1992
Sylhet Hills	249	1.3×10^{-5}	HTS/MMP 1967
Barind Tract	1,835	1.6×10^{-2}	Ahmed 1994

Sources: after UNDP 1982; BGS and DPHE 2001.

TABLE 14. Freshwater resources and withdrawals in Bangladesh.

Renewable freshwater resources		
Precipitation (long-term average)	2,320	mm/yr
Internal renewable water resources (long-term average)	105,000	Mm^3/yr
Total actual renewable water resources	1,226,600	Mm^3/yr
Total actual renewable water resources per inhabitant	8,343	m^3/yr
Total dam capacity	20,300	Mm^3
Water withdrawals		
Total water withdrawals	35,870	Mm^3/yr
Irrigation + livestock	31,500	Mm^3/yr
Municipalities	3,600	Mm^3/yr
Industry	770	Mm^3/yr
Per inhabitant	247	m^3/yr
Surface water and groundwater withdrawals	35,870	Mm^3/yr

Source: after FAO 2011.

Groundwater Quality

In Bangladesh, groundwater usage has increased tremendously due to the limited availability of surface water, especially during the dry season. Groundwater is a source of water for irrigation, municipal and industrial uses. The major groundwater issues are the impact of groundwater pumping for irrigation, pollution by cities and industries, degradation of water quality by agricultural activities, salinity intrusion and arsenic contamination (Zahid and Ahmed 2006). According to Zahid and Ahmed (2006), heavy metals in soils and sediments are increased in many areas of Bangladesh due to industrial activities. The discharge of tannery effluents directly into nature causes accumulation of Cr, Al and Fe in topsoils with a significant quantity of Mn, Zn, Ni and Cu which are leached from the soils and affect groundwater quality. Low level of organochlorine pesticides (Heptachlor and dichlorodiphenyltrichloroethane [DDT]) and higher ammonium and nitrate levels have been found in the shallow aquifers, which highlights the impact of fertilizer and pesticide use in the agriculture sector (Hossain 1997).

Seawater intrusion is also encountered in the coastal plain aquifer of Bangladesh. Deep aquifer is a potential source of fresh groundwater, below a sequence of other aquifer layers containing saline or brackish groundwater (DPHE-DANIDA 2001). Groundwater abstraction mostly takes place from the upper aquifer in the southern regions of Bangladesh. Intensive pumping of groundwater for irrigation and other uses from the shallow unconfined aquifers in coastal areas causes widespread saltwater intrusion, downward leakage of arsenic concentrations and the general degradation of water resources. Arsenic contamination of groundwater in Bangladesh has been studied by several agencies (Government of Bangladesh [GoB]; Ground Water Task Force [GWTF]; Department of Public Health Engineering (DPHE), Bangladesh; British Geological Survey [BGS]; United Nations Children's Fund [UNICEF]; World Bank [WB]; and Food and Agriculture Organization of the United Nations [FAO]). They reported that 61 out of 64 districts, especially water from STW and HTW, were contaminated by arsenic. Maximum arsenic concentration has been identified within the upper 50 m depth of aquifers in most regions (Jones 2000).

Nepal

General

Nepal is located in the Ganges Basin and the total land area is 147,180 km^2. According to a survey in 2011, the total population is 26.494 million inhabitants (86% of which live in rural areas) and 50.27% live in the Terai region (Central Bureau of Statistics, Nepal). Physiographically, the country can be divided into three parts: the high Himalayas in the North (24% of the country's total area); the hill and mountain slopes in the center (56%), which include the lower hills called Siwalik where elevations vary between 300 and 700 m; and the plain called Terai in the South at elevations below 300 m (20%). The Nepal Terai Plain is the northern extension of the Gangetic Plain and is about 30 km in width. In Nepal, the cultivable area is estimated to be about 4 Mha, of which 34% is in the Terai plain. Nepal experiences tropical, meso-thermal, micro-thermal, taiga and tundra types of climate. The average annual rainfall is 1,500 mm and the southwest monsoon brings more than 75% of the total rainfall. The minimum and maximum temperature are -14.6 °C and 44 °C, respectively. Due to adequate water supplies in the Terai, the cultivation of three crops a year is very common.

Geology and Lithology

The Gangetic Plain in the Nepalese portion is referred to as the Terai Zone that extends from the Indian Shield in the South to the sub-Himalayan (Siwalik) Zone in the North. According to Sharma (1981, 1995) and Dahal (2006), the Nepal Terai comprises a significant thickness of alluvial clays and silts with important but subordinate sand and gravel layers. The unconsolidated strata of alluvium overlie the Siwalik sequence. It is a leaky aquifer, with vertical exchange between shallow and deep confined aquifers, dependent upon thickness and lateral persistence of the low permeability beds. In the South, the aquifer material is predominantly sands composed of finer sediments, while the aquifers in the North are predominantly gravels. Dahal (2006) reported that the Terai Zone is in less than 200 m amsl and usually has thick (nearly 1,500 m) alluvial sediments. The alluvial sediments contain mainly boulder, gravel, silt and clay. The width of the Terai Zone varies from 10 to 50 km and forms a nearly continuous belt from East to West, except at two places, Chitwan and Rapti valleys, where the Terai Zone is interrupted by Siwalik for 70 km and 80 km, respectively. The Terai Zone is a foreland basin and has sediment originating from peaks of the northern part (Dahal 2006). Based on the borehole logs, geophysical investigation and petroleum exploration studies in the Terai, it is classified into Northern Terai or Bhabhar Zone, Middle Terai and Southern Terai.

The Northern Terai (Bhabhar Zone) is adjoining the foothills of Siwalik and continues southward to a maximum width of 12 km. This zone is mainly composed of boulders, pebbles, cobbles and coarse sand derived from the rocks of Siwalik and Lesser Himalaya, and acts as a recharge zone for the groundwater of the Terai. In this Zone, water tables in wells show very sharp fluctuations between the summer and rainy seasons, and wells become completely dry in some places during the summer. This zone is not productive for agriculture due to the very coarse nature of the sediments, low water table and quick percolation of rainwater.

Middle Terai is a narrow zone about 10-12 km wide and lying in the middle of the Northern Terai Zone and the Southern Terai Zone. It is characterized by pebbly and brown to grey colored unconsolidated sandy sediments with few clay partings. The medium to coarse grained sandy layers show a good groundwater reservoir. This zone shows a marked development of spring line, natural ponds, marshland and lakes due to a change in elevation from the Bhabar Zone (Dahal 2006).

There are many artesian layers found in depths of 25 m to 200 m immediately south of spring lines. The permeability of this zone decreases towards the South and, finally, non-permeable layers are encountered in the boundary of the Southern Terai Zone.

Southern Terai Zone is the southernmost part of the Terai up to the Nepal-India border and also continues into India. It consists of main sediments of the Gangetic Plain. Basically, sand, silt and clay are the main sediments of this zone. These aquifers are poor and the water table is about 3 mbgl. Good aquifers are found in the old river channel areas.

Groundwater Potential and Challenges

Nepal is divided into five river basins from West to East: Mahakali, Karnali, Gandaki, Kosi and the southern river basins. Southern river basins produce some 65 km^3/year of water flowing into India (Wells and Dorr 1987; FAO 2011). Mahakali River Basin is shared with India with an average flow of 15 km^3/year and receives 3.4 km^3/year of water from the Nepalese tributaries (FAO 2011). In the Karnali River Basin, the average outflow is estimated to be 43.9 km^3/year. The average flow in the Gandaki River Basin is 50.7 km^3/year. In the Kosi River Basin, average outflow is 47.2 km^3/year. Surface water resources in Nepal is estimated to be 198.2 km^3/year. The Kosi River in the Eastern Ganga Plains is one of the most avulsive river systems in the world ('avulsion' is the natural process by which flow diverts out of an established river channel into a new permanent course on the adjacent floodplain). The river's transport capacity may at times be exceeded due to the relatively high sediment yields from basins that alternate between dry and wet seasons (Wells and Dorr 1987). Rao and Prasad (1994) reported that Koshi and Gandak rivers, formed from snowmelt, have constant interaction with groundwater, which contributes to a substantial part of the flow of these rivers during the non-monsoon period. Groundwater found in the Terai region is both under confined and unconfined conditions. Groundwater under an unconfined condition is formed by the clayey sand and sandy formation down to an average depth of 50 m. Groundwater under a confined condition exists in sand-gravel beds at depths below 50 m. In the flowing wells, the piezometric head is from 6.60 to 8.90 meters above ground level (magl) and in the non-flowing wells it is from 1.65 to 11.20 mbgl. In the flowing wells (TW), the yield is from 25 to 55 1ps for a pressure head varying from 1.5 m to 8.7 m. In the non-flowing wells, the discharge is between 8.86 and 37.94 lps at drawdowns from 4 to 9 m.

FAO (2011) reported that groundwater resources have not been fully assessed in the Nepal Terai. Ongoing studies show that there is good potential for groundwater extraction, especially in the Southern Terai lowland plains and inner valleys of the hilly and mountainous regions. Much of the Terai physiographic region is underlain by deep or shallow aquifers, many of which are suitable for exploitation as sources of irrigation water. According to GWRDB (2012), dynamic groundwater resources are 8,800 Mm^3 and the abstraction for irrigation/industrial uses and drinking purposes are 756 Mm^3 and 297 Mm^3, respectively. The groundwater balance is 7,747 Mm^3, which is a surplus. According to Jain et al. (2009) and WECS (2004), the stage of groundwater development is 10%. Total renewable water resources of this country are 210.2 Bm^3/year and the capacity of all existing dams in Nepal is 85 Mm^3 (FAO 2011). In Nepal, total water withdrawals are 9.79 Bm^3/year, which is 4.7% of total actual renewable water resources. According to FAO (2011), 67% and 39% of the population live in urban and rural areas, respectively, and receive piped domestic water supply based on a 1992 survey. The available land area for surface water irrigation is 2,177,800 ha.

Groundwater Quality

In the Nepal Terai, 11.2 million people depend on groundwater for drinking purposes and irrigation (Khan and Tater 2006). In the Terai region, the quality of shallow groundwater depends, to a large extent, on the lithology of the sediments (BGS 2001). Anaerobic conditions are observed in some parts of the shallow aquifer of the Terai, which have high concentrations of arsenic and iron. In the Terai, several groundwater quality surveys indicated that arsenic in some samples exceeds desirable limits. The Department of Water Supply and Sewerage (DWSS) found 1% of water sources analyzed had arsenic concentrations greater than 50 µg/l (BGS 2001). Maximum concentrations were recorded in groundwater in the active floodplain of the River Koshi. The Nepal Red Cross Society (NRCS), from testing groundwater in 17 of the 20 Terai districts, found that approximately 3% of the samples had concentrations above 50 µg/l. The highest observed concentration was 205 µg/l and the worst affected districts were Nawalparasi (western region), Rautahat and Bara (central region), and Bardia (midwestern region). NRCS (2001) has listed these districts, together with Parsa, Rupandehi, Kapilbastu and Banke, as priority areas for testing, water-supply mitigation and health screening. Tandukar (2001) reported that the maximum arsenic concentrations recorded was 120 µg/l, and most of the high arsenic levels were recorded in samples from the River Bagmati area.

Groundwater Potential of the EGB

Table 15 provides details of the overall groundwater potential in the Eastern Ganges Basin. It shows that net groundwater availability is 135.30 Bm^3 and irrigation consumes 34.79% of groundwater availability. The annual groundwater draft for irrigation and other uses is 54.26 Bm^3 and the stage of groundwater development is 40%. These statistics imply that the available groundwater is not utilized completely and also shows the existence of enormous untapped groundwater resources. As mentioned earlier, 80% of the total population living in the rural areas depend on agriculture for their livelihoods. Further, vast areas of agricultural land are plain and fertile. Hence, proper planning for groundwater management will enhance agricultural production, and will help in reducing poverty and ensuring food security.

TABLE 15. Estimated dynamic groundwater resources availability, utilization and stage of development in the Eastern Ganges Basin.

Country	Groundwater availability (Bm^3)	Annual groundwater draft (Bm^3)			Stage of groundwater development (%)
		Irrigation	Domestic, industrial and other uses	Total	
India (three states)	59.2	21.07	2.79	23.86	40
Nepal	11.50	0.80	0.30	1.10	10
Bangladesh	64.6	25.2	4.1	29.3	45
Total	*135.3*	*47.07*	*7.19*	*54.26*	*40*

Sources: Compiled from CGWB 2011; Jain et al. 2009; BADC 2007; BMDA 2004; Hossain et al. 2002; WECS 2004.

CONCLUSIONS

The present study elucidates the groundwater resources and hydrogeological conditions in the Eastern Ganges Basin (EGB) using published and unpublished literature and documents containing data relevant to these topics. The EGB covers the states of Bihar, Jharkhand and West Bengal in India, and Bangladesh and the Nepal Terai. The Ganges Basin is the most populated river basin in the world. In the EGB, 80% of the total population live in rural areas and depend on agriculture for their livelihoods. The average annual discharge of Ganga River is 16,650 m^3/s. Groundwater potential in the Ganges Basin (India, Bangladesh and Nepal) is 244.8 Bm^3. The EGB has enormous surface water and vast untapped groundwater resources which are not being properly utilized. Regulation, water access, low electrification, high cost of diesel and scattered landings are major constraints for agricultural productivity improvement in this region.

The EGB experiences a tropical monsoon climate. Rainfall in this basin is highly variable and mainly occurs during the southwest monsoon between June and September. The average annual rainfall varies from 1,063 mm (Jharkhand) to 2,500 mm (West Bengal (North)). Geological and lithological information suggest that this basin is comprised of unconsolidated/alluvial formation, semi-consolidated formations and consolidated/fissured formation. Most of the area in this basin is covered by alluvial formation deposited by the Ganga and Brahmaputra rivers, which masked the basement rocks. Lithology and groundwater potential of this basin reveal the existence of a multilayered aquifer with high-yielding properties. Groundwater occurs under unconfined, semi-confined and confined conditions. Estimated dynamic groundwater resources in the Indian part of the EGB indicate that annual replenishable groundwater resources, net groundwater availability and groundwater draft for all purposes are 65.09 Bm^3, 59.2 Bm^3 and 23.86 Bm^3, respectively. In Bangladesh, the available groundwater resources and groundwater draft are 64.6 Bm^3 and 29.3 Bm^3, respectively. In Nepal, groundwater availability is 11.5 Bm^3 and annual groundwater draft is 1.10 Bm^3. The overall groundwater availability in the EGB is 135.3 Bm^3 and only 34.79% of this is utilized for irrigation. The stage of groundwater development is 40%. These statistics imply that existing groundwater is not used appropriately and large space is available for groundwater development in this region. Moreover, vast plain and fertile lands are available for agriculture. The groundwater quality in the EGB is also suitable for irrigation. Groundwater quality issues were identified in a few parts of the EGB. The major contaminants identified in the groundwater are arsenic and fluoride followed by iron, chloride and salinity. However, proper planning and management will be required to utilize the surplus groundwater potential for agriculture, which will enhance food production and reduce poverty in the Eastern Ganges Basin.

Hydrogeology maps for Bangladesh, Nepal and Jharkhand are not available or accessible in the literature, which may be due to the lack of data availability in these regions. The groundwater exploration studies in the southern part of Jharkhand and coastal/southern part of Bangladesh are limited. In India, most of the groundwater exploration studies were conducted by the Central Ground Water Board (CGWB), India, and some by state groundwater boards. Except for these two sources, acquiring data was limited. According to the knowledge of the authors, this is the first report that has been compiled with complete details of the hydrogeology and groundwater resource potential of the Eastern Ganges Basin. This report will act as a base for any future work related to groundwater development, management and modeling in this basin. Future research may concentrate on three objectives: (i) creating a database for the EGB using regional data; ii) hydrogeology map of the whole of the EGB; and iii) groundwater modeling for the entire EGB. The outcome of these research activities will support groundwater development and management in the region.

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