Groundwater Governance in the Indo-Gangetic and Yellow River Basins

Realities and Challenges

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A comparative analysis of the hydrogeology of the Indus-Gangetic and Yellow River basins

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ABSTRACT: The Indus, Gangetic and Yellow River basins have supported thriving agriculture economies from time immemorial. Of late, unplanned over-exploitation of their resources, especially groundwater, has raised concerns about the long-term hydrological sustainability of the irrigated agriculture in the region. This calls for a fresh look at the hydrogeological resources and the management options for these basins. The Indus basin with a drainage area of 1.1 M km^2 supports the world's largest contiguous irrigation system called the Indus Basin Irrigation System. In both the Indus Basin and western parts of the Gangetic basin, there is intensive use of groundwater and this has led to a decline in the groundwater table. In the eastern part of the Gangetic basin groundwater is relatively under utilized. The Huang-Huai-Hai plain of the Yellow River Basin is one of the largest groundwater irrigated regions in China and produces the bulk of China's food grains.

1 INTRODUCTION

The Indus-Gangetic basin and the Yellow River basin have large surface and groundwater resources and support some of the oldest civilizations in the world. Both the basins have thriving irrigated economies and the surplus food produced in the basins ensures food security for the region (India, Pakistan, Bangladesh, Nepal and China). The Indus basin has the world's largest continuous surface irrigation system and the Ganges and Yellow Rivers also support vast canal networks. However, since the 1980s, the runaway growth in groundwater tubewells has outpaced surface irrigation. This has created an agrarian boom with massive productivity and livelihood benefits (Shah et al., 2003). However, such a phenomenal growth over a short period has also created several problems including a decline in water tables over large areas, increase in energy requirements for extracting groundwater, emergence of groundwater quality issues such as salinity, nitrate, fluoride and arsenic in groundwater and intrusion of sea water into coastal areas. At the same time there are regional imbalances in groundwater exploitation with vast untapped groundwater potential in the eastern Ganges basin and southern parts of the Yellow river basin. All these existing and emerging problems of groundwater governance and management require a better understanding of the hydrogeology.

2 THE INDUS AND GANGES RIVER BASIN

The Indus basin is one of the largest river basins in Asia extending over four countries, China, Afghanistan, Pakistan and India. The Indus River Basin is 3,199 km long with a basin area of about 1.1 million km^2 of which 63% of the area is in Pakistan, 29% in India and the rest 8% is shared between China and Afghanistan (IUCN, 2005; Fig. 1). The drainage area within Pakistan is 692,700 km^2. According to a 2001 estimate (UNESCO, 2001) the population of the basin is 150 million. However, Fahlbusch et al. (2004) placed the population at 196 million.

The annual flow of the entire Indus river system ranges from 120 billion m^3 to 230 billion m^3 (41 year average, 1957–1997). The mean annual system inflows are 175 billion m^3 with a coefficient of variability of 13%. About 83% of the flow occurs during the monsoon months (April to September). There is not much yearly variation in the system inflow during the winter *rabi* season (Khan, 1999). The Indus Basin Irrigation System (IBIS) of Pakistan is the largest integrated irrigation network in the world, serving 17 million hectares of land. In the Indian part of the Indus basin, an average annual surface water potential of 73.3 km^3 has been assessed. Out of this, only about 46.0 km^3 is utilizable.

The Ganga River is one of most important rivers of India and is considered sacred by its majority Hindu population. The Ganga basin extends over an area of 1,089,370 km^2. It flows through four countries, namely India (79.2%), Nepal (12.85%), Tibet (China) (3.67%), and Bangladesh (4.28%). The total length of the Ganga River is 2,525 km (Fig. 2). The Ganga basin is one of the most densely populated regions of the world. The average population density is 550 persons/km^2 and about 42% of India's population lives in this basin.

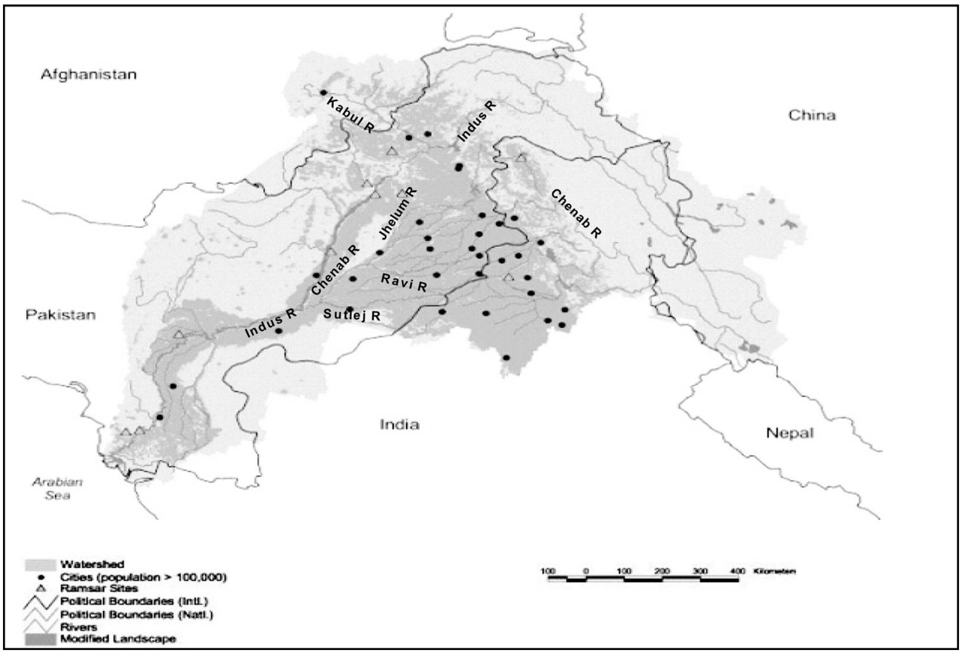

Figure 1. Indus Basin map (Revenga et al., 1998) (See colour plate section).

The average annual discharge of the Ganga River is 16,650 m^3/s. The surface water resource potential of the Ganga and its tributaries in India has been assessed at 525 billion m^3 out of which 250 billion m^3 is considered to be useable. There are large temporal variations in the flow. The Ganga River carries one of the world's highest sediment loads, equal to nearly 1,451 million metric tons per annum. Figure 3 shows the annual discharge of Ganga at Farakka for the period 1950 to 1985 (Jain et al., 2007).

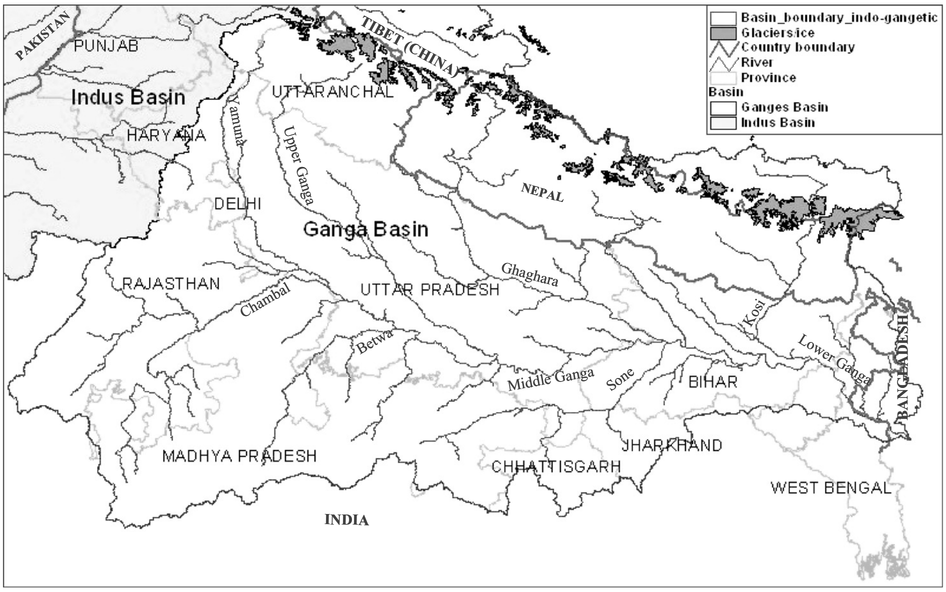

Figure 2. Ganga Basin map (IWMI 2008, available at http://dw.iwmi.org/) (See colour plate section).

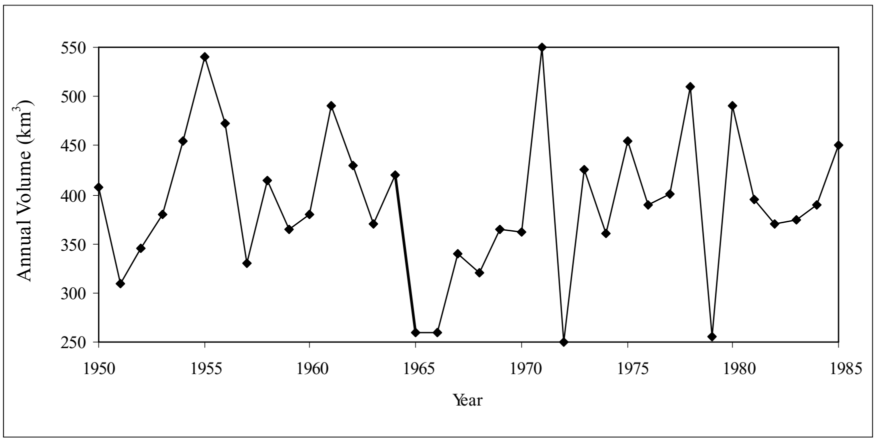

Figure 3. Annual discharge of Ganga at Farakka (Rogers et al., 1989).

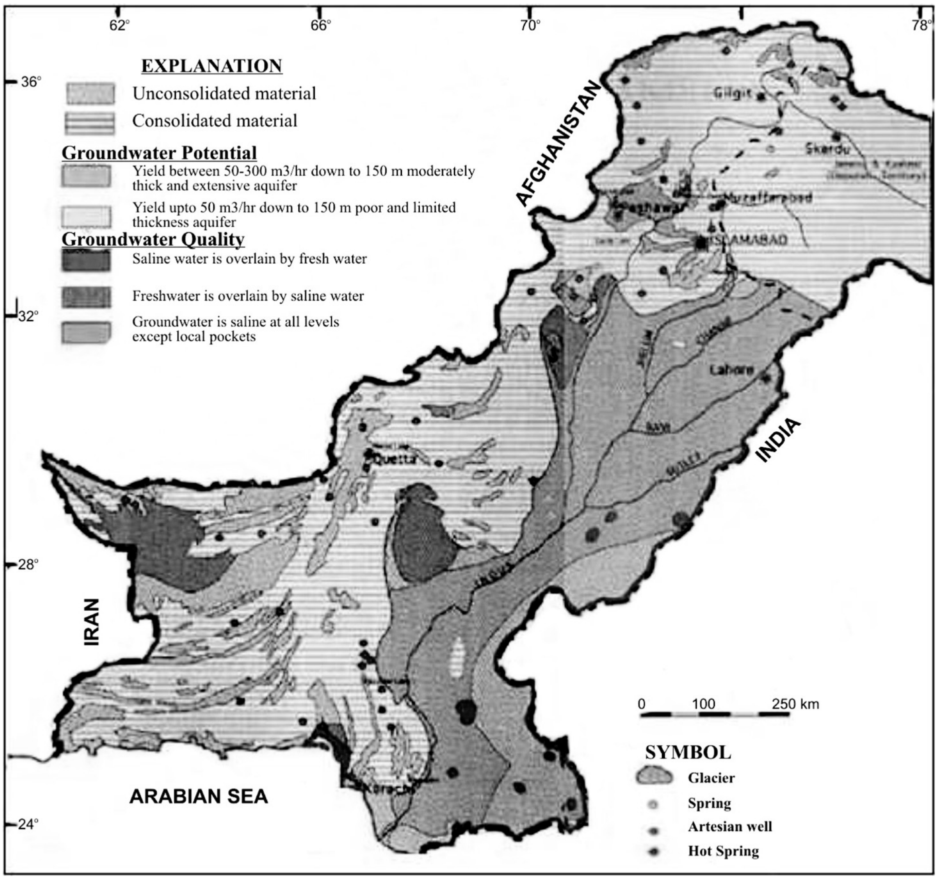

Figure 4. Hydrogeology map of Pakistan (Geological Survey of Pakistan, 2000) (See colour plate section).

2.1 *Hydrogeology of Indus and Ganga basins*

2.1.1 *Hydrogeology of Indus in Pakistan*

The geology of the Indus Basin is dominated by Quaternary sediments which are often hundreds of metres thick. The Indus sediments are mainly alluvial and deltaic deposits, consisting of fine-to medium-grained sand, silt and clay. Coarser sands and gravels occur on the margins of the plain abutting upland areas (WAPDA/EUAD, 1989). Wind-blown sands occur to the east of the Indus Plain (Thar and Cholistan desert areas). Mesozoic and Cenozoic sedimentary rocks occur in a north-south tract to the west of the Indus Plain stretching from Peshawar to the coast. Older (palaeozoic) sediments and crystalline basement rocks (granites, metamorphic rocks) are mainly restricted to the north, including North West Frontier Province, Gilgit and Jammu and Kashmir.

Groundwater yields from these sediments are typically around 50–300 m^3/hour down to 150 m depth. Lower yields (up to 50 m^3/hour) are obtained from the sediments of the Thar and Cholistan desert regions on the eastern fringes of the Plain (south-eastern border with India)—see Figure 4. Yields are also restricted in the fine-grained Quaternary tidal and deltaic deposits in the southern coastal area (Shamsi, 1989). A district level study across the country by NESPAK (1991) reported a specific yield of 0.09 to 0.2. These estimates broadly show a high yielding aquifer with a substantial storage capacity. Before the introduction of surface irrigation systems, groundwater tables in the Indus Plain were typically 20–30 m deep. Over the years, water levels in the aquifers have risen significantly as a result of increased recharge from earthen canals and irrigated fields. Waterlogging with accompanying salinisation of groundwater has become a major problem in parts of the Indus Plain.

Groundwater is important for irrigated agriculture, which allows for an extensive exploitation and recycling over the major portion of the Indus Basin. Irrigated land provides 90% by value of Pakistan's agricultural production, and accounts for 25% of its gross domestic product (GDP) and employs 60% of the labour force.

2.1.2 *Hydrogeology of Indus-Ganges Basin in India*

Hydrogeologically, the Indo-Gangetic basin from north to south is divisible into six regions, namely, the Himalayan region, sub-Himalayan region, Bhabar zone, Tarai zone, Central Ganga Plains (CGP) and marginal alluvial plains.

The Himalayan Region confined between the Siwalik range in the south and the Zanskar range in the north represents hilly and rugged terrain consisting of a variety of rock formations, which are continuously undergoing disintegration through glacio-fluvial action. Larger part of this region remains under snow cover throughout the year. The Great Himalayas are the gathering grounds which feed a multitude of glaciers, some of which are among the largest in the world outside the Polar circles (Wadia, 1990). The Indus basin has the largest number of glaciers (3,538), followed by the Ganga basin (1,020) and the Brahmaputra (662) (WWF, 2005). The inter-granular pore spaces, openings, fissures, fractures, joints and bedding planes developed promote the infiltration of rainwater which reappears down slope as spring and seepage (Valdiya and Bartarya, 1989). Here groundwater occurs in the secondary porosity of the formation and is unconfined.

The sub-Himalayan region lies to the south of the Himalayan zone and is occupied by the Siwalik ranges. They form a system of low foothills with an average height of 900–1,500 m (Wadia, 1990). The groundwater here mostly is unconfined and sometimes semi-confined. The depth to the water table ranges between 10 and 20 m below ground level (bgl). The tubewells are reported to be capable of yielding 50 to 80 m^3/hr in Siwaliks of Uttarakhand and 100 to 120 m^3/hr in the inter-montane valleys in Himachal Pradesh (CGWB, 2008). The coefficient of permeability varies between 15 and 250 m/day.

The northern belt of the Indo-Gangetic alluvial tract (near the Himalayan foothills) is characterized by coarse materials (principally boulder-gravel) forming the piedmont terrain. It is referred to as *Bhabar* in Uttar Pradesh and *Kandi* in Jammu & Kashmir and Punjab. This formation has been formed by lateral coalescence of alluvial cone and fan deposits brought down by innumerable streams (Wadia, 1990). The rivers crossing Bhabar lose large quantity of flow to the gravels. Groundwater is unconfined and the water table is deep (30 m or more). The groundwater has a hydraulic gradient of around 3 m/km. The hydraulic conductivity ranges between 25 to 250 m/day. The Bhabars are capable of yielding about 100–300 m^3/hr of water (CGWB, 2008).

The Bhabar belt is overlain by the Terai belt of stratified bands of dominantly coarse sediments with clay. This occupies a narrow belt and its contact with the Bhabar is well marked by a spring line. The presence of highly porous and permeable fan deposits ensures

Table 1. Aquifer variables in Central Ganga Plain (Karanth, 1987).

S.No.	Parameter	Right bank aquifer	Left bank aquifer
1	Transmissivity (m^2/day)	520	3530
2	Storage coefficient	1.13×10^{-3}	1.5×10^{-3}
3	Hydraulic conductivity (m/day)	37	55

large supplies of groundwater from the *Terai* belt for agricultural and industrial use. The *Terai* has an upper unconfined aquifer and a lower interconnected system of confined aquifers. Between the *Bhabar* and the confined aquifers of the *Terai* belt is a vast zone where recharge is encouraged by high rainfall and hilly streams. The piezometric head of the aquifer ranges between 6 to 9 m above ground level. The coefficient of permeability ranges between 17 and 108 m/day. The yield of tubewells tapping the *Terai* zones ranges between 50–200 m^3/hr (CGWB, 2008).

The Central Ganga plain forms one of the richest aquifers of the world. The typical channel deposit of the Ganga River, from the bottom upward, comprises coarse sand mixed with gravel, medium-to fine—grained sand to silt and a capping of thin clay. This clay cap and some fine sand layers are washed away during the flood period, and a fresh body of sand with a fining upward sequence is deposited again each year during the flood, thus building up a thick terrigenous clastic deposit until the river next changes its course. In the Central Ganga Plains, extensive exploratory studies have indicated the presence of four aquifer groups within a depth of 700 m bgl. The individual aquifers vary in thickness from a few meters up to 300 m. Although locally separated, aquifers are hydraulically connected at a regional scale (Karanth, 1987). The range of aquifer parameters in the Central Ganga Plains is shown in Table 1. Groundwater occurs under water table conditions in the shallow aquifers, and is semi-confined to confined in the deeper aquifers. The yield of tubewells in this area ranges between 90–200 m^3/hr (CGWB, 2008).

CGWB (1984) mapped the Upper Yamuna Basin (UYB) showing different potential aquifer groups up to a depth of 450 m. The regional picture of sub-surface geology revealed the existence of three aquifer systems. Table 2 presents the profile and aquifer characteristics of these three systems.

2.1.3 *Hydrogeology of Ganges in Nepal Terai*

The Nepal *Terai* plain is the northern extension of Gangetic plain and is about 30 km in width. It comprises a significant thickness of alluvial clays and silts with important but subordinate sand and gravel layers. In the foothills, the basement hard rocks are believed to be at depth of 4–6 km. The overlying Eocene-Pliocene deposits are an upward coarsening gently northward dipping sequence of sedimentary rocks of the Siwaliks (shale, sandstone conglomerate) of about 2 km thickness. The unconsolidated strata of alluvium overlie the Siwalik sequence. The thickness exceeds the maximum depth of the investigatory drilling at around 500 m. 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 (Sharma, 1984, 1995). In the south the aquifers material is predominantly sands, while the aquifers in the north are predominantly gravels. Further, south the aquifer material is composed of finer sediments. The static water level in the south is at around 3 to 5 m,

Table 2. Aquifer parameters of UYB area (CGWB, 1984).

Parameter	Range	Average values
Aquifer group—I		
Profile: Extend up to 167 m bgl over the basin and underlain by a clayey horizon, 10–15 m thick, except in the foothill region. The group is unconfined and semi-confined		
Transmissivity (m^2/day)	800–5,210	2,200
Lateral hydraulic conductivity 'K' (m/day)	14–47	24
Specific yield (S_y)%	6–24	12
Aquifer group—II		
Profile: Numerous sand and clay lenses occurring at variable depth (65–283 m bgl). Sediments are less coarse and are occasionally mixed with gravel (*kankar*). Ground water occurs under confined to semi-confined conditions. Aquifer is underlain by another clayey horizon of considerably thick at places and appears to be regionally extensive.		
Transmissivity (m^2/day)	750–1,050	700
Lateral hydraulic conductivity 'K' (m/day)	4–11	7.2
Storativity	5.6×10^{-4} to 1.7×10^{-3}	1.0×10^{-3}
Specific yield (S_y)%	3.35×10^{-4} to 2.7×10^{-3}	1.9×10^{-3}
Aquifer group—III		
Profile: Thin sand layers alternating with thicker clay layers occurring at variable depths (197–346 m bgl). The granular material is generally finer in texture. Kankar occurs in the southern parts. Groundwater normally occurs under confined conditions.		
Transmissivity (m^2/day)	345–830	525
Lateral hydraulic conductivity 'K' (m/day)	3.5–10.7	7.1
Storativity	6.6×10^{-4} to 2.4×10^{-4}	4.5×10^{-4}

while in the north it is between 6 m to over 10 m depth. The drawdown in the south is comparatively small compared to the northern part (Figure 5).

2.1.4 *Hydrogeology of Ganges Basin in Bangladesh*

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). The basin comprises geosynclinal deposits of late Cretaceous age and a thick sequence of Tertiary marine continental deposits. Immense sedimentation took place in the Ganges-Brahmaputra-Meghna delta complex during the Cenozoic time and more than half of it was deposited during the Plio-Pleistocene and Holocene time leading to the southward growth and development of the Bengal Delta. Much of the sediment is deposited by the Ganga-Brahmaputra-Meghna (GBM) river systems during Miocene to Holocene time. Holocene floodplain deposits cover most of the surface area of present-day Bangladesh. Arsenic contamination mainly occurs at shallow depths beneath the Holocene floodplains. The area is underlain by poorly consolidated or unconsolidated sediments of Tertiary and Quaternary ages.

The tropical monsoon climate with favorable geological and hydrogeologic conditions ensures very high potential storage of groundwater in Bangladesh. Major aquifer systems belong to the Late Pleistocene Holocene sediments. In the floodplains of the major rivers and the delta plain of the GBM Delta Complex regions, major aquifer systems

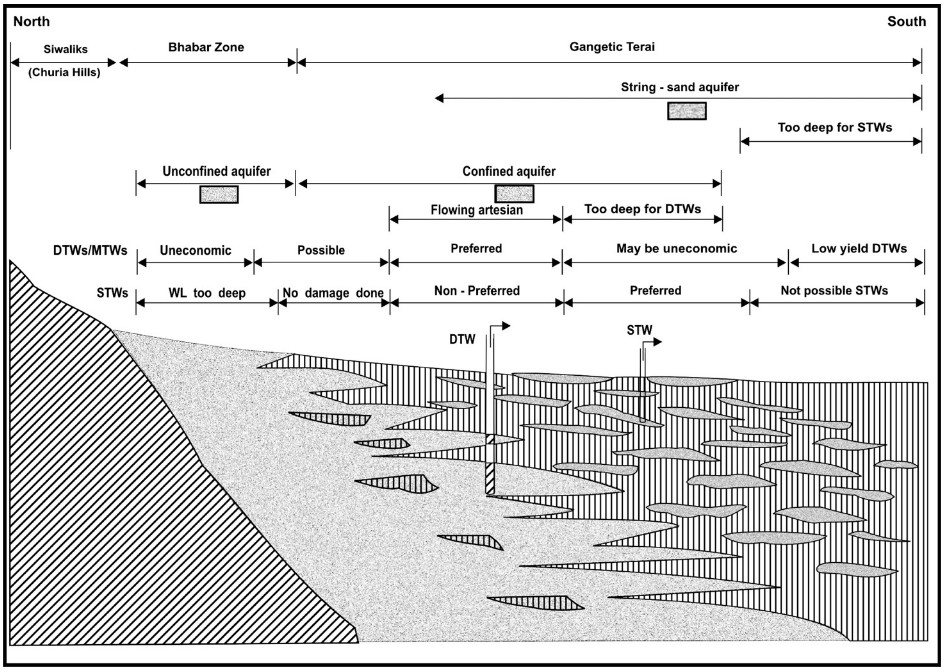

Figure 5. Schematic cross section through the aquifer system of main Terai plains (Sharma, 1995).

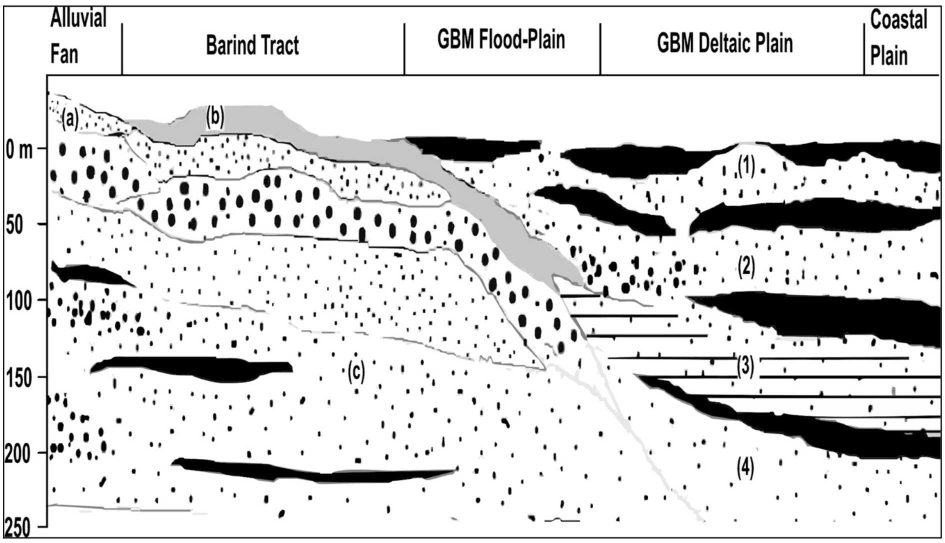

Figure 6. Distribution of BWDB-UNDP aquifers (BWDB-UNDP, 1982).

Table 3. Aquifer properties in the shallow and main aquifers in Bangladesh (BWDB, 1994, 1989).

	Transmissivity (m^2/day)		Storage co-efficient		Permeability(m/day)	
Regions	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
North-East	200	3000	0.002	0.10	3	90
North-West	300	4000	0.003	0.23	12	114
South-West	900	3200	0.010	0.15	11	6.5
South-East	140	1900	0.0007	0.07	5	23

occur in the Late Pleistocene to Holocene sediments. In part of the southeast region multi-layered aquifer conditions exist. On a regional basis BWDB-UNDP (1982) described three aquifers between Holocene and Plio-Pleistocene formations. These are the 1) Upper Shallower or the Composite Aquifer, 2) Main Aquifer, and 3) Deep Aquifer (Figure 6). The aquifer sediments are composed of very fine to fine sand, in places inter-bedded or mixed with medium sand in very thin layers. Discontinuous thin clay layers often separate these sand layers. In the coastal region water in this aquifer zone is saline with occasional fresh water pockets. Water in this layer is severely contaminated by arsenic. Beneath the composite aquifer, the main aquifer occurs at depths ranging from less than 5 m in the northwest to 140 m in the south east and is generally underlain and overlain by a silty clay bed. In the Meghna floodplain areas it up to 300 m deep (Zahid and Hassan, 2007) and in large areas of the Pleistocene terraces, the main aquifer is encountered below 75–300 m. This aquifer is comprised of medium-and coarse-grained sediments, in places inter bedded with gravel. It is either semi-confined/leaky or consists of stratified interconnected, unconfined water-bearing zones. Irrigation water is drawn predominantly from these strata.

The deep aquifer is separated from the overlying main aquifer by one or more clay layers of varied thickness. Geologically and hydro-stratigraphically the deeper aquifer (Holocene/Late Pleistocene) is separated by impermeable or leaky clay/silty clay layers from the upper alluvial aquifer (GWTF, 2002). The depth of the deep aquifers varies from region to region depending on the geology and depositional environment of the sediment. This aquifer comprises mainly grey to dark grey fine- to medium-grained sand that in places alternates with thin sandy shale/clay lenses. The aquifer properties for the shallow and deep aquifers are given in Table 3, and for the different physiographic units existing in the Ganges dependent areas in Table 4.

2.2 *Groundwater resources of Indus and Ganga basins*

Groundwater resources can be classified as static and dynamic. The static resource is the amount of groundwater available in the permeable portion of the aquifer below the zone of water level fluctuation. The dynamic resource is the amount of groundwater available in the zone of water level fluctuation. Sustainable groundwater development requires that only the dynamic resources are tapped. Exploitation of static groundwater resources could be considered during extreme conditions, but only for essential purposes. The static fresh groundwater resource of the Indus and Ganga basin are listed in Table 5.

Table 4. Physiographic units and acquifer types of the Ganges dependent district of Bangladesh.

Physiographic unit	District	Lithology	Aquifer (Type/Thickness/Depth)	Aquifer properties
Northwest Region Ganges (*Ganges flood plain, ridges and basins*)	Rajshahi, Pabna	Silty clay bands occur to over 30 m in places thin sand lenses common with small aquifer potential. Below 30 m, coarser sediments with 70 m or more thickness	• Semi-confined • Thickness Range: 10–70 m • Average Depth Range: 30–35 m	Transmissivity (m^2/day) *Regional*: 300–4000 Rajshahi: 418–2399 Pabna: 1200–4000 Storativity *Regional*: 0.003–0.23 Rajshahi: .0003–0.10 Pabna: 0.04–0.10 Permeability (m/day) *Regional*: 11–114 Rajshahi: 14–40 Pabna: 26–82
Southwest Region Old Gangetic Floodplain (*Part of Gangetic moribund delta with linear ridges comprising of level to very gently undulating levees, inter ridge depressions and stream beds of dominant topographic elements*)	Kushtia, Jessore, Faridpur, Khulna	Predominantly medium-to coarse-grained, well sorted sand grading upward to fine sand to silty sand and clay with distinct fining up sequences. Capped by 10 to 60 m silty/sandy surface clay	• Extremely unconfined, locally semi-confined and confined • Thickness: around 100 m; • Depth: 10 to 60 m with an average of 30 m	Transmissivity (m^2/day) *Regional*: 900–3200 Jessore: 161–2300 Khustia: 710–2500 Faridpur: 900–2300
Young Gangetic Floodplain (*Meander floodplains landscape of ridges, young channels and widespread development of past basins*)	Faridpur, Khulna, Barisal	Medium to fine grained sand constitutes the suffer materials. 30–60 m of surface clay with abundant peat layers covers the aquifer	• Semi-confined to unconfined, locally multiple • Thickness: average 55 m • Depth: averages 40 m	Storativity *Regional*: 0.01–0.15 Jessore: 0.004–0.07 Khustia: 0.007–0.252 Faridpur: 0.01–0.15
Coastal Plain (*Coastal deltaic plain with mangrove forest*)	Khulna, Barisal Patuakhali	Extensive thick surface clay up to 90 m, locally up to 150 m. Well defined aquifer of coarse-to medium-grained sand locally occurs at depths between 225 to 325 m with extensive clay cover	• Confined and multiple	Permeability (m/day) *Regional*: 11–65 Jessore: 24–31 Khustia: 15–35 Faridpur: 11–36

Source: GWTF, 2002.

Table 5. Static fresh ground water fesource (km^3) of IG Basin (CGWB, 1999).

River basin	Alluvium/ Unconsolidated rocks	Hard rocks	Total
Indus	1,334.9	3.3	1,338.2
Ganga	7,769.1	65	7,834.1

Groundwater resources in the Ganga basin are nearly six times that of the Indus basin. The dynamic groundwater resources of different Indian states which fall in the Indo-Gangetic basin are listed in Table 6. Table 7 shows the comparative analysis of groundwater availability and consumption in three basin countries. The Ganga basin falls under 'safe' category on (GW development <70%) compared to the Indus basin (over-exploited category) based their status of groundwater development. This implies that annual groundwater consumption is more than the annual groundwater available in the Indus basin.

3 YELLOW RIVER BASIN (YRB)

The Yellow River, the sixth longest river in the world and second longest river in China, is the "Cradle of Ancient Chinese civilization", because human inhabitants have existed in this region since prehistoric times (Wang et al., 2000). The Yellow River is 5,464 km long with a basin area of 794,712 km^2. It is a home to a population of over 171.9 million (NBS, 1999). It flows from the high mountain areas as high as 4,500 m in Qinghai, eastward from Gansu, Ningxia Hui, Inner Mongolian, Shanxi, Shaanxi, Henan, Hebei and Shandong, and into the Bohai Sea (Yellow sea). The Yellow River water contains sediment concentration as high as 35 kg/m^3 on average after it flows across the loess plateau. The lower reaches of the Yellow River flow through the North China Plain formed by the flooding deposits from the Huang (Yellow) River, the Hai River and the Huai River. The lower channel is about 700 km long through the Huang-Huai-Hai Plain . Flooding occurred 1500 times during the past 2000 years, because of the instability of the river. Fortunately, the flooding problem has been almost controlled in the past five decades with the construction of levees and flow regulation.

The average flow rate of the river is 58 billion m^3/yr, of which 56% is from the upstream of Lanzhou. Long term annual precipitation in the Yellow River Basin is 452 mm which is unevenly distributed in time and space. Rainfall ranging from 60 to 80% of the annual total occurs between July and October, while only 10 to 20% precipitation takes places during the growing season of winter wheat (March to May). The mean annual evaporation ranges from 1,000 to 3,000 mm. The total water resource is 70.7 billion m^3/yr. Water availability per capita is in the order of 428 to 647 m^3 and irrigation water availability per ha is in the order of 3,765–4,350 m^3/ha. Table 8 shows water resources in the Yellow River and Huang-Huai-Hai plain. Per capita water resource availability is low, varying from 121 to 428 m^3/year.

3.1 *Hydrogeological characteristics of the Yellow River Basin*

Geologically, the Yellow River Basin covers three large geotectonic units: the north China platform, Qinling-Qilian-Kunlun geosyncline and Yunnan-Tibet geosyncline.

Table 6. Estimated dynamic groundwater resources availability, utilization and stage of development in the Indo-Gangetic Basin (Indian part) CGWB (2006).

State	Annual replenishable GW resources (bcm)	Natrual discharge (bcm)	Net GW avail. (bcm)	Annual groundwater draft (bcm)			Stage of GW development (%)
				Iriig.	Domestic & industrial	Total	
Ganga Basin							
Bihar	29.19	1.77	27.42	9.39	1.37	10.76	39
Chattisgarh	5.70	0.45	5.25	0.89	0.22	1.11	21
Delhi	0.30	0.02	0.28	0.20	0.28	0.48	171
Haryana	6.79	0.51	6.28	6.94	0.24	7.18	114
Himachal Pradesh	0.08	0.01	0.07	0.007	0.003	0.01	14
Jharkhand	3.53	0.20	3.33	0.54	0.23	0.77	23
Madhya Pradesh	27.50	1.37	26.13	13.04	0.80	13.84	53
Rajasthan	7.73	0.74	6.99	7.9	0.915	8.815	126
Uttar Pradesh	76.35	6.17	70.18	45.36	3.42	48.78	70
Uttaranchal	2.27	0.17	2.10	1.34	0.05	1.39	66
West Bengal	22.85	2.18	20.67	8.83	0.62	9.45	46
Total	182.29	13.59	168.70	94.44	8.15	102.35	61
Indus Basin							
Haryana	4.15	0.28	3.87	3.69	0.12	3.81	98
Himachal Pradesh	0.35	0.03	0.32	0.08	0.017	0.10	31
Jammu & Kashmir	2.70	0.27	2.43	0.10	0.24	0.34	14
Punjab	23.78	2.34	21.44	30.34	0.83	31.17	145
Rajasthan	2.33	0.23	2.10	2.18	0.39	2.57	122
Total	33.31	3.15	30.16	36.39	1.60	38	126

Table 7. Estimated groundwater availability and use in the Indus and Ganga Basins (CGWB (2006), BADC (2007), BMDA (2004), Hossain et al., (2002), WECS (2004)).

Basin name	Groundwater available (bcm)	Annual groundwater draft (bcm) Irrigation	Domestic, industrial & others	Total	Stage of GW development (%)
Ganga Basin					
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
	244.8	120.4	12.6	132.8	54
Indus Basin					
India	30.2	36.4	1.6	38.0	126
Pakistan*	55.1	46.2	5.1	51.3	93
	85.3	82.6	6.7	89.3	105

* It is assumed that 90% of groundwater use is consumed by irrigation sector.

Table 8. Water resources in the Yellow River and Huang-Huai-Hai plain in 2002[1] (Jin et al., 2006).

Catchments/ regions	Rainfall (billion m^3/yr)	Surface water (billion m^3/yr)	Ground water (billion m^3/yr)	Water deducted[2] (billion m^3/yr)	Total water resources (billion m^3/yr)	Per capita water res. (m^3)
Hai-river Basin	127.381	6.408	14.609	9.491	15.899	121
Huai-river Basin	237.591	44.536	34.366	25.647	70.183	343
Yellow River Basin	322.487	35.766	33.401	11.574	47.340	428
Total	6261.029	2724.329	869.718	101.701	2826.130	2200

Notes: [1] Data from the Annual report of 2002 by the Ministry of Water Resources PR China. [2] The water deducted is the water volume that has to be subtracted from the sum of surface and groundwater due to the interrelation between surface water and groundwater.

Geomorphologically the basin covers the Qinghai plateau, Loess Plateau and Huang-Huai-Hai plains. These control the occurrence of groundwater in the basin (Lin & Wang 2006; Chen & Cai 2000). Areas covered by the three geotectonic units in the basin are in the raio of 6:3:1. Considering the characteristics of geotectonic units, the north China platform has the best conditions for groundwater occurrence. The Qinling-Qilian-Kunlun geosyncline and Yunnan-Tibet geosyncline underwent fierce tectonic movements and generated many folds and faults, and aquifers tend to be small in area. Figure 7 and Table 9 show regional availability of groundwater in the Yellow River Basin and the Huang-Huai-Hai plain.

In the Yellow River Basin groundwater may be intergranular, contained in secondary porosity, and there is some karst. Intergranular storage occurs mainly in the Huang-Huai-Hai plain, alluvial plain of the main branches of the Yellow River and the intermountain basins. The main aquifers consist of sand, gravel and cobble grade material of Quaternary age and occur. Fracture storage is widespread in the hilly regions and Cenozoic basins of upstream and middle reach of the Yellow River Basin. Karst rocks are mainly distributed in the caves and fractures of Cambrian and Ordovician carbonates in Luliang mountain, Taihang mountain, Zhongtiao mountain, Tai Mountain and eastern part of Qinling. Fracture storage in magmatic and metamorphic rocks mainly occurs in weathering material in the mountain and hilly regions of the basin.

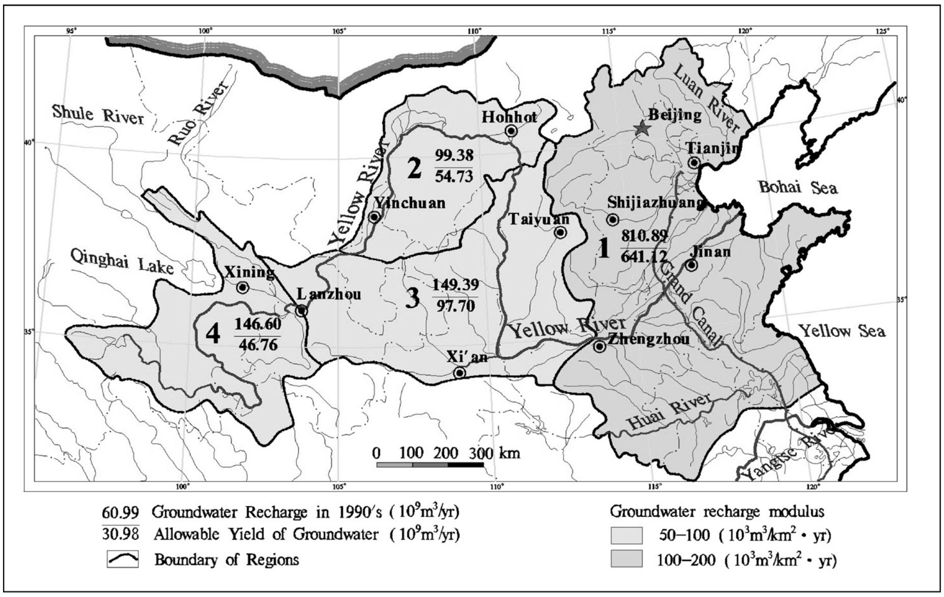

Figure 7. Groundwater resources in the Yellow River basin and the Huang-Huai-Hai plain (See colour plate section).

Table 9. Available groundwater resources in Yellow River basin and Huang-Huai-Hai plain[1].

Regions		Groundwater recharge (bcm/yr)	Groundwater recharge (10^3 $m^3/km^2 \cdot yr$)	Allowable yield of groundwater (bcm/yr)	Allowable yield of groundwater (10^3 $m^3/km^2 \cdot yr$)
	1. Huang-Huai-Hai plain	63.533	114.6	51.210	101.8
Yellow River catchments	1. Lower reaches of Yellow River[2]	4.045	162.2	4.053	162.1
	2. Ordos plateau and Yinchuan plain	7.285	56.1	3.958	31.4
	3. Loess plateau	13.054	54.2	9.375	64.0
	4. Upper reaches of Yellow River	14.144	62.5	4.378	20.9
	Sum	38.528	61.1	21.764	43.0

Notes: [1] Data from Ministry of Land and Resources, China, 2003; [2] The number of Huang-Huai-Hai plain includes 4.045 bcm/yr of the lower reaches of Yellow River; [3] Location see Figure 7.
Source: Jin et al., 2006.

3.1.1 *Hydrogeology of the Ordos Basin*

The Loess Plateau has an area of 614,700 km^2, and covers seven provinces of China including most of the Yellow River Basin. It is a comparatively water scarce area. The Ordos Basin is typical of the Loess Plateau.

The Ordos Basin is located in the east of northwestern China with an area of 275,000 km^2 and covers five provinces, i.e. Shaanxi, Gansu, Ningxia, Inner Mongolia and Shanxi (Wang et al., 2005). The total water resource in the basin is about 28.9 billion m^3/year. Allowable groundwater abstraction is 12.91 billion m^3/year. Current water use is about 22.96 billion m^3/year, in which contribution from groundwater is 5.23 billion m^3/year. Water demand in 2010 is estimated at 35.36 billion m^3/year (Wang et al., 2005).

There are four kinds of aquifers in the Ordos Basin: the Quaternary intergranular aquifer, Cretaceous fracture aquifer system, Carboniferous-Jurassic fracture aquifer system and Cambrian-Ordovician Carbonate Karst aquifer system (Fig. 8). All of these aquifer systems are superimposed vertically and connected laterally. There is a close hydraulic connection among these aquifer systems, which makes the Ordos Basin a semi-open groundwater basin (Hou et al., 2006).

Quaternary intergranular aquifer system overlies the Jurassic-Carboniferous rocks consisting of Pleistocene sand which is 60–80 m thick. It is generally in hydraulic connection with the underlying Jurassic aquifer. Water quality is generally good with TDS less than 1000 mg/l and pumping rates up to 40–125 m^3/hour.

Cretaceous fractured aquifer system in the middle-west part of the Ordos Basin is a sub-sedimentary basin overlying the Jurassic and pre-Mesozoic basin. It is artesian and is recharged by surface water and lateral recharge and flows towards rivers. There are no regional aquicludes in the system which is about 1,000 m thick.

Carboniferous-Jurassic fracture aquifer system lies between the Cambrian-Ordovician Karst aquifer system and the Cretaceous aquifer system covering an area of 64,700 km^2. It mainly comprises alternate layers of sandstones and mudstones. Due to cementation, the well yield rate is low. Direct rainfall recharge takes place in the shallow or weathered zones (50–100 m depth). The Carboniferous-Jurassic aquifers in thew river valleys are interconnected with the Quaternary system with good quality and high yielding rates in river valleys.

The Karst aquifer system of Cambrian-Ordovician Carbonate rocks mainly outcrops along the margins of the Ordos basin and is confined by the overlying Carboniferous aluminous shale. More than 70% of the recharge is from direct rainfall recharge and groundwater flows westward parallel to the outcrop. The discharge is in the form of large springs in the sections where the aquifer is cut by the Yellow River and its tributaries. The higher yielding locations are mainly in the lower reaches in the west where most of wells are artisan with yield rates of 1,000 and 10,000 m^3/d, exceptionally up to 50,000 m^3/d. The water quality is good with total dissolved solids less than 1000 mg/l.

3.1.2 *Hydrogeology in Huang-Huai-Hai plain*

Huang-Huai-Hai plain is one of the largest food production regions in China, with an area of 310,000 km^2 (the north of the Yellow River of the plains is also called North China plains, with an area of 134,780 km^2). Groundwater in the Quaternary aquifer system is the principal source for water supply in the plains due to the scarcity of surface water (Fig. 9).

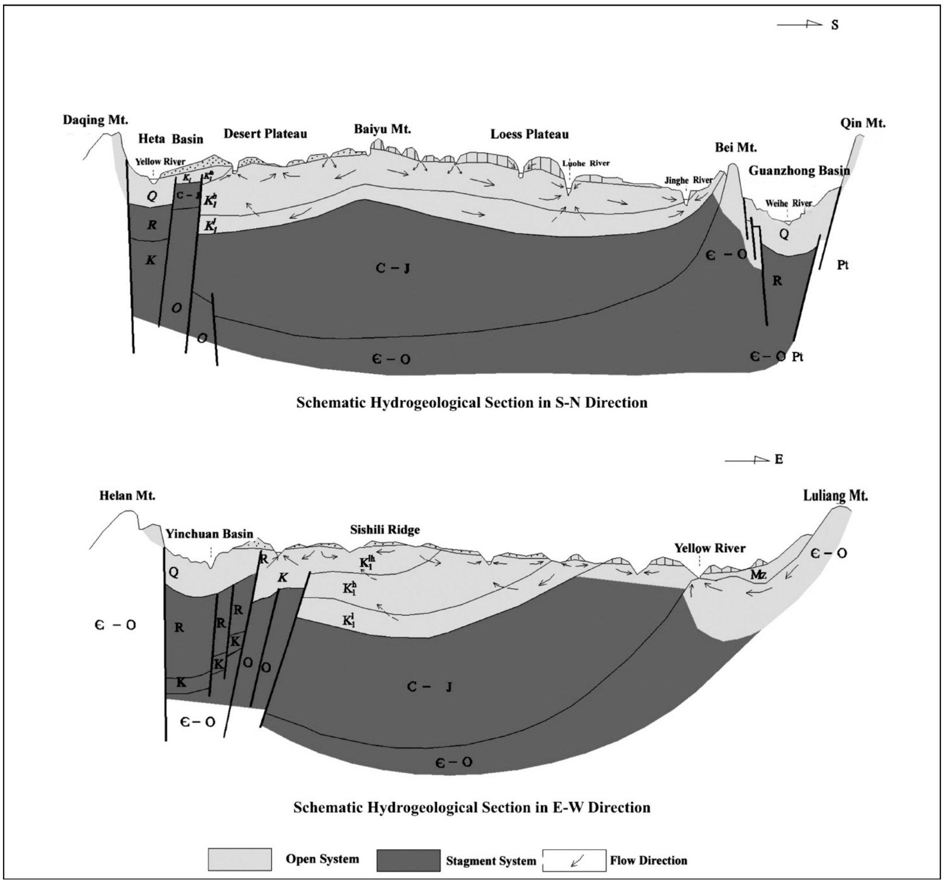

Figure 8. Hydrogeological section of the Ordos Basin (Wang et al., 2005; Hou et al., 2006).

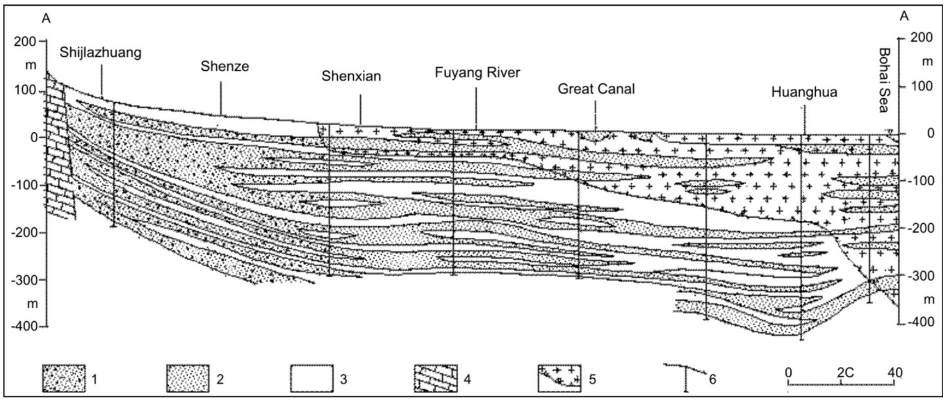

Figure 9. Profile of the North China plain (Zhang et al., 1994).
1-gravel and sand; 2-sand; 3-clayey soil; 4-carbonate rock; 5-saline water (TDS>2 g/L); 6-borehole.

Groundwater in the west piedmont plain is fresh water (TDS is les than 2000 mg/l). The aquifers are mainly composed of sand and gravel with clayey and loam layers. The fluvial-lacustrine plain is mainly clayey with some sand units. There is a widespread layer of saline water between 50 and 120 m in thickness and of 2000–10,000 mg/l TDS. The groundwater above the saline water is called the shallow fresh water and below the saline water is deep fresh water.

In the east fluvial-marine plain there are clayey beds with intermediate sand layers. There is a marine saline layer 100–300 m in thickness with the TDS reaching a maximum of 35,000 mg/l. There is little shallow fresh water in the fluvial-marine plain, but some fresh water occurs at depth.

Long-term over-extraction of groundwater has resulted in serious environmental degradation such as a continuous decline in groundwater levels resulting from over-exploitation. The rate of decline is 1–2 m/yr for many deep freshwater aquifers and the bottom of the saline water is moving down towards the deep fresh water; land subsidence and degradation of water quality (harmful ions are released during consolidation of the aquitards (clay).

3.2 *Groundwater resources in the Yellow River Basin*

The total water use in the Yellow River Basin was 51.2 billion m^3 in 2006. Total groundwater abstraction in the YRB in 2006 was 13.7 billion m^3, of which 6.9 billion m^3 (50.2%), was for irrigation purposes (Table 10).

4 COMPARATIVE ANALYSIS OF INDUS, GANGETIC AND YELLOW RIVER BASINS

Table 11 presents the overall comparative picture of Indus, Gangetic and Yellow River Basins based on some common parameters. Both the Indus and Gages drain vast areas of more than 1 million sq. km. and as such support well developed surface and groundwater based irrigation systems. Availability of water resources both on a per capita basis and per hectare cultivated is on the decline in all the three basins with its impact most severely felt in the Yellow River Basin followed by the Indus and Gangetic basins. Complex interactions lead to widespread distribution of salinity and fluoride problems in the Indus Basin and the release of arsenic in the lower parts of the Ganges Basin. The aquifers in the Yellow River Basin are threatened by industrial and domestic pollutants. Vast regions of rice and wheat are threatened due to the continuous decline of the water table in the Indus, the western Ganges and Yellow River basins. The eastern Ganges basin still provides an opportunity to harness the available surface and groundwater resources for a more stable, improved and diversified agricultural production system. Decreasing water supplies, increasing demand and a rapidly growing economy have added new challenges to the management agenda. Urgent supply and demand interventions are needed to mediate this gap in sustainability. These include integrated use of surface and groundwater resources, development of groundwater in less exploited areas, selected and need based development of deeper aquifers, safe use of saline and brackish aquifers, enhanced and coordinated efforts for recharge and conservation projects and practices, aligning cropping patterns with water resource availability and improving water productivity at all levels- field, farm, project and basin.

Table 10. Composition of groundwater use (billion m^3) in YRB in 2006 (YRCC, 2007).

Regions			Groundwater use					
Users	Total water use	GW use	Agriculture irrigation	Forest, livestock	Industry	Urban public	Urban domestic	Eco-environment
Up Longyangxia	0.21	0.014	/	0.002	0.003	0.004	0.005	/
Longyangxia-Lanzhou	3.69	0.627	0.141	0.003	0.306	0.046	0.110	0.021
Lanzhou–Toudaoguai	18.53	2.602	1.268	0.271	0.677	0.095	0.257	0.034
Toudaoguai-Longmen	1.75	0.709	0.356	0.064	0.178	0.015	0.090	0.006
Longmen-Sanmenxia	10.13	5.472	2.618	0.390	1.418	0.208	0.799	0.039
Sanmenxia-Huayuankou	3.85	1.769	0.658	0.096	0.672	0.044	0.245	0.054
Down-Huayuankou	12.72	2.319	1.725	0.172	0.159	0.019	0.237	0.007
Inland drainage area	0.33	0.206	0.123	0.060	0.011	/	0.010	/
Total	51.21	13.718	6.889	1.058	3.424	0.431	1.753	0.161
Percentage	100	26.79	50.22	7.71	24.96	3.14	12.78	1.17

Table 11. Comparison of Indus, Gangetic and Yellow River Basins.

Parameters	Ganga	Indus	Yellow
Length (km); Drainage area (km^2)	Length–2,525; D.A.–1,089,370	Length–3,199; D.A.–1,029,089	Length–5,464; D.A.–794,712
Country	India, Nepal, Bangladesh, Tibet (China)	Pakistan, India, Afghanistan, China	China
Population (million)	600	150	172
Altitude range	7,010 m to the sea	5,182 m to the sea	5,400 m to the sea
Climate	Hot and Subhumid	Semi-arid	Arid, semi-arid
Rainfall (mm)	up to 1000 (Western part), above 1800 (Eastern and lower part)	400–800	360–380 (Upper), 456–570 (Middle), 614–733 (Lower)
Mean inflow (bcm)	525	175	58
Irrigated area (million ha)	19.5	14.6	7.5
Sediment load (billion ton)	0.73 (at Farakka)	0.2	1.6
Erosion processes	*Himalaya*: Landslides, glaciation, channel, sheet and rill, glacier lake-burst floods (GLOFs), and landslide lake-burst floods (LLFs) *Siwalik*: Landslides, sheet and rill, channel *Plain*: Sheet and rill, channel, wind	Landslides, glaciation, rill, gully, stream bank, pinnacle, wind	*Loess plateau*: Sheet, gully, Debris flow, Landslide, Funnel, wind blowing, Ice-melt (mainly concentrated in middle reach of YRB)
Lithology	*Himalaya*: Crystalline, sedimentary, and meta sedimentary rocks *Terai Bhabar belt*: Boulder, cobble, pebble, gravels, sands, silt and clays *Siwalik*: Sedimentary rocks, often partly lithified *Plain*: Unconsolidated alluvium and aeolian deposits (Clays & silts, gravels & sands, lenses of peat & organic matter, carbonate and siliceous concretions (Kankar) *Floodplain & Delta*: Aquifer of grey medium to course sands capped by 10–60 m surface clay, Silty clay, peat	Young (Quaternary) Alluvial and deltaic deposits, consisting mainly of fine-medium sand, silt and clay; Older (palaeozoic) sediments and crystalline basement rocks are restricted to north (Gilgit and J&K)	North China platform (60%) followed by Qinling-Qilian-Kunlun geosyncline and Yunnan-Tibet geosyncline; Large area of unconsolidated Quaternary (down-stream); sedimentary formation of geosynclinal clastic rock and volcanic rock, along with metamorphic rock (upstream)

(*Continued*)

Table 11. (*Continued*)

Parameters	Ganga	Indus	Yellow
Aquifer characteristics	*Central plain*: Transmissivity (m^2/d): 520–3530 Storage coefficient: $1.13 \times 10^{-3} - 1.5 \times 10^{-3}$ Hydraulic conductivity (m/d): 37–55 *Floodplain & Delta*: Transmissivity (m^2/d): 1000–5000 Storage coefficient: $1.13 \times 10^{-3} - 1.5 \times 10^{-3}$ Hydraulic conductivity (m/d): 11–114	Plains between Ravi and Chenab rivers: Hydraulic conductivity: 47–120 m/day Specific yield: 0.01–0.13 Groundwater salinity: 500–1000 μS/m	Transmissivity (m^2/d): 100–5000 Storage coefficient: 0.01–0.25 Hydraulic conductivity (m/d): 0.1–50
Groundwater yield (m^3/hr)	*Bhabar* : 100–300; *Tarai*: 100–200; *Central plain*: 90–200; *Floodplain & Delta*: 50–200	*Alluvial plain*: 100–300 *Coastal area*: up to 50	40–210
Net annual GW available (mcm/km^2)	0.225	0.083	0.027
Net annual groundwater draft (mcm/km^2)	0.122	0.086	0.017
Stage of groundwater development (%)	54	105	63
Dependency of irrigation on GW (%)	91	92.5	50
GW quality	*Salinity*: Haryana, Rajasthan (western Ganga) *Arsenic*: West Bengal and Bengal delta plains in Bangladesh	*Salinity*: Punjab and part of lower Indus basin *Arsenic*: Part of Punjab and Sindh	*Salinity*: Ningxia and Inner Mongolia areas (middle reach) *Arsenic*: Shan Xi Province and Inner Mongolia

Groundwater in the Indus-Gangetic and Yellow River basins offer great opportunities for sustaining the livelihoods of about one billion people. Better use of the resource can be achieved by improved domestic socio-economic and policy environments in the respective countries (India, Nepal and Bangladesh and China) and also through a shared modern, transparent and real-time data management system on resource availability, abstraction, quality, and other hydrogeological variables.

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