21 Review on Sustainable Groundwater Development and Management Strategies Associated with the Largest Alluvial Multi-aquifer Systems of Indo-Gangetic Basin in India

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Abstract

Demand for groundwater for various uses is increasing rapidly due to accelerated growth of population, industrialization, irrigation, and urbanization. Availability of limited surface water resources is the reason for ever-increasing demand for groundwater. The diminishing quantity of replenishable groundwater resources in the unconfined, as well as confined aquifers, is facilitating the depletion of groundwater table in the Indo-Gangetic Basin (IGB). Hence, the assessment of the availability of groundwater resources is of immense importance to develop a sustainable management plan. The IGB covers an area of 1,182,689 km^2 which forms the single largest groundwater reservoir with prolific multi-aquifer systems. The basin stretches over the northern zone from west to east below the extra-peninsular region of India. The tube wells tapping deeper confined aquifers have potential yields ranging between 25 and 50 Liters per second (lps) at economic drawdown. The study reveals that a total of about 1750.92 BCM of groundwater resources are available in the alluvial area of 466,007 km^2. of IGB, of which around >91% is fresh and around 9% is brackish/saline. In 2002, arsenic in groundwater in the IGB was first detected beyond the permissible limit (>50 µg/l). But, around two decades ago arsenic menace was identified in the downstream area of IGB in the Bengal Basin and in the belt of Ganga-Meghna-Brahmaputra (GMB) River system. The severity of arsenic hazards in the Bengal Basin is considered one of the drastic health hazards. Groundwater Estimation Committee (GEC), 2015 methodology report of Central Ground Water Board (CGWB) indicates that the net annual groundwater availability of IGB is 180.38 billion cubic meters (BCM) and annual groundwater draft for domestic, industries, and irrigation uses amounts to 140.77 BCM. The stage of groundwater development is recorded as the minimum (23%) in Jharkhand state, whereas the maximum (149%) is in Punjab state. The excess exploitation and occurrence of high arsenic in shallow aquifers pose a threat to the sustainable management of groundwater resources in the IGB.

Keywords

Indo-Gangetic Basin · Replenishable groundwater assessment · Arsenic contamination · Sustainable management

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21.1 Introduction

Indo-Gangetic basin covers an area of 1,182,689 km^2 (Indus basin: 321,289 km^2 and Ganga basin: 861,400 km^2). The basin lies within the coordinates of 27°0′0″ N and 80°0′0″ E. The study area encompasses 09 states and 01 Union Territory (U.T.) comprising the Haryana, Punjab, Himachal Pradesh, Rajasthan, Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, and West Bengal states and Delhi U.T. (Fig. 21.1). It constitutes the single largest groundwater reservoir with a prolific multi-aquifer system stretched over the northern zone of India and is characterized by the distinctive facies associations of gravelly fan deposits, sandy and muddy interfluves deposits, and river channel deposits (Singh 1996). Longer residential period of the river channels had facilitated to build a huge pile of sand bodies in the basin. Fine sand successions have been developed in the interfluves region, which is categorized as flood plain deposits. The basin forms the significant part of ancient continent of Gondwana and is portrayed as the oldest and most geologically stable plain of the country (After Britannica.com/Gondwana). The IGB had attained its present shape during the late Quaternary period. In Indian sub-continent, the basin includes mostly northern and eastern portions of India followed by the east of Pakistan, almost entire Bangladesh, and southern plains of Nepal. It witnesses diversified geomorphological features, grain size variations, and channel pattern changes.

The fertile Indo-Gangetic alluvial plain hosts a huge quantity of freshwater resources as it has been formed due to deposition of sand and silt by numerous rivers like Ganga, Yamuna, and Brahmaputra originating from the Himalaya Mountains. The vast alluvial tract of the basin maintains a wide range in altitude from <01 m at *Sundarbans* to within 200–375 m at Uttar Pradesh and Haryana and within 150–450 m in Rajasthan. The Tertiary and Quaternary sediments in the foreland IGB overlie different older litho units in different parts of the foredeep in either the metamorphosed basement rocks, the undifferentiated un-metamorphosed Proterozoic sediments and the Gondwana Mesozoic sediments. The basement topography has a number of highs and lows traversed by several faults, which have affected the deposition of Tertiary and Quaternary sediments. In general, 2000–5000 m thick Siwalik (Tertiary) sediments of the foreland basin are underlying the alluvial plain. The thickness of these sediments increases toward north, being maximum along the northern margin, along the Himalayan foothills, and minimum in the southern margin over the Vindhyans or Bundelkhand massif (Singh 1996).

The groundwater resources of the replenishable zone have already been separately computed as dynamic groundwater resources of the basin. The present study aims at estimating the monsoon and non-monsoon recharges, replenishable groundwater resources, draft for various uses, calculation of stage of groundwater development percentage for different state/U.T. lying within the IGB along with recommendations for area specific sustainable groundwater management strategies.

21.2 Methodology Adopted for the Study

The dynamic groundwater resources of the unconfined aquifer have been estimated using the methodology that is defined by the Groundwater Estimation Committee (GEC) in 2015 by Central Ground Water Board. Adopted values of specific yield (0.6) for assessment of in-storage resources of the unconfined aquifers were considered for computing the dynamic resources of the unconfined aquifer. The aquifer system has been broadly classified into two groups viz. unconfined and confined. The extrapolation of the confined aquifer has been carried out by considering the maximum depth of exploration, used for the computation of the groundwater resources of the unconfined aquifers. Other data like the average depth of the predominant pre-monsoon water level (for the last 10 years) of unconfined aquifers of each district has been considered as

Fig. 21.1 Location map of Indo-Gangetic River Basin. *Source* GSI

top of in-storage portion of the unconfined aquifer. On other hand, the district-wise bottom of the unconfined aquifer was determined with the help of the groundwater exploration carried out by CGWB in all the states having Indo-Gangetic alluvium, and also on the basis of lithological and geophysical logs.

The average depth of the bottom of unconfined aquifer in each district and district-wise thickness of unconfined aquifers have been considered for computation of in-storage resources. Thickness of the unconfined aquifer was derived by subtracting average bottom depth of unconfined aquifer from predominant pre-monsoon groundwater levels. District-wise thickness of granular zones in the unconfined aquifers was estimated based on the interpretations of lithological logs, and electrical logs of the exploratory wells drilled by CGWB. The inter-layering of clay in unconfined and confined aquifers has been considered as single unit for computation purposes. The continuity of the various aquifer parameters such as specific yield and storativity co-efficient was taken into account while computing groundwater resources for unconfined and confined aquifers across the state borders.

The continuity of other inputs like bottom of unconfined aquifer and extension were checked and established with the neighboring districts of other states (after CGWB). Specific yield values, which have been considered for estimating dynamic groundwater resources of unconfined aquifers, by keeping in view of the reduction in the specific yield values due to increase in consolidation/compaction with depth and also the uncertainties in litho-facies variation. An attempt has been made for computing the groundwater resources for fresh and brackish/saline water separately as far as possible.

21.3 The Indo-Gangetic Plain and Aquifer System

The Indo-Gangetic Plain (IGP) is one of the most important regions of India; consists of alluvium with vast groundwater storage capacity. Based on climatic, hydrologic, and physiographic variations, the IGP consists of five homogeneous regions: (1) Trans-Gangetic plain in Pakistan; (2) Trans-Gangetic plain in India; (3) Upper-Gangetic plain; (4) Middle-Gangetic plain; and

(5) Lower-Gangetic plain. The basin is divided into four distinct physiographic zones, viz. Trans Indo-Gangetic Plains (TIGP), Upper Indo-Gangetic Plains (UIGP), Middle Indo-Gangetic Plains (MIGP), and Lower Indo-Gangetic Plains (LIGP) (Shah 2014). The strategy to develop static resources of alluvial aquifers needs a precise and sound understanding of the disposition of subsurface aquifer system and overall hydrogeological scenario. Below the zone of water table fluctuation, the groundwater, which is available in the perennially saturated zones, forms the in-storage groundwater resources of the unconfined aquifer.

A confined aquifer consists of porous and permeable geological formation, which is sandwiched in between two relatively low permeability layers. The confining layers above and below the confined aquifer are regionally extensive. The recharge and discharge areas of these aquifers may be hundreds of kilometers apart. The groundwater development in confined aquifers is much more complicated than in unconfined aquifers, due to their typical hydrogeological characteristics and hydraulic properties. In case of confined aquifer, the release of groundwater initially starts from the storage components and later on by the compression of the aquifer skeleton followed by the expansion of groundwater. This mechanism is exclusively controlled by the elastic properties of aquifer material. In the unconfined aquifer, the water releasing process is highly associated with the desaturation of the aquifer skeleton in the phreatic zone. Assessment of groundwater development potential for confined aquifers assume of crucial importance, since over-exploitation of these aquifers may lead to far more adverse consequences. And, of the 1068 blocks (groundwater development units) in the three states (Punjab, Haryana, and Uttar Pradesh), 214 were characterized as dark or gray (groundwater extraction exceeds the annual recharge) in the context of groundwater depletion (Kamra 2007). The CGWB (2017) demonstrated that the entire IGB region (Fig. 21.2) depicted an abstraction ratio of >75 (Amarasinghe et al. 2016). The Projected demand for domestic and industrial uses in 2025 would be around 13.21 BCM, of which maximum demands are to be claimed by Uttar Pradesh (6.44 BCM) and minimum by Himachal Pradesh (0.07 BCM).

Central Ground Water Board (CGWB) conducted the detailed hydro-geochemical survey to understand the groundwater quality of the shallow aquifer system in the IGB. The study was appreciable enough to delineate the shallow aquifers affected by the arsenic severity (Fig. 21.3). The severity of arsenic contamination in shallow aquifers is mainly restricted in the Bengal Delta within the Holocene Younger Delta Plain and the alluvial formations, which have been approximately deposited during the period of 10,000–7000 years BP. The phenomenon may be associated with the Holocene sea-level rise and simultaneous rapid erosion in the Himalayan region (Acharyya et al. 2007).

21.3.1 Sediment Deposition History

In the broad depression and in sub-basins over the floor of the Ganga foreland basin, deposition took place during the Upper Tertiary and Quaternary periods. The depositional history in the foredeep gives an insight into the sedimentation process that occurred in different geological time scales along with subsequent digenesis. Initiation of the sedimentation mainly took place in a narrow-elongated foreland basin with the deposition of Dharmshala-Muree sediments in early Miocene period and was restricted in this narrow basin close to the Himalayan orogen. During middle Miocene to middle Pleistocene the orogen ward part of the foreland basin sediments was uplifted and thrusted toward the basin in discrete steps, while the basin expanded toward the craton (Fig. 21.4). Thus, the Siwalik sediments thickened toward foothills due to the greater load of sediments and greater concomitant sinking of the basin floor in that direction.

Thickness wise the foreland basin sediments show a strong asymmetry. Overlap of the younger Siwalik toward the south is an indication of widening of the basin over the Bundelkhand massif, whereas sediments of Middle and Upper

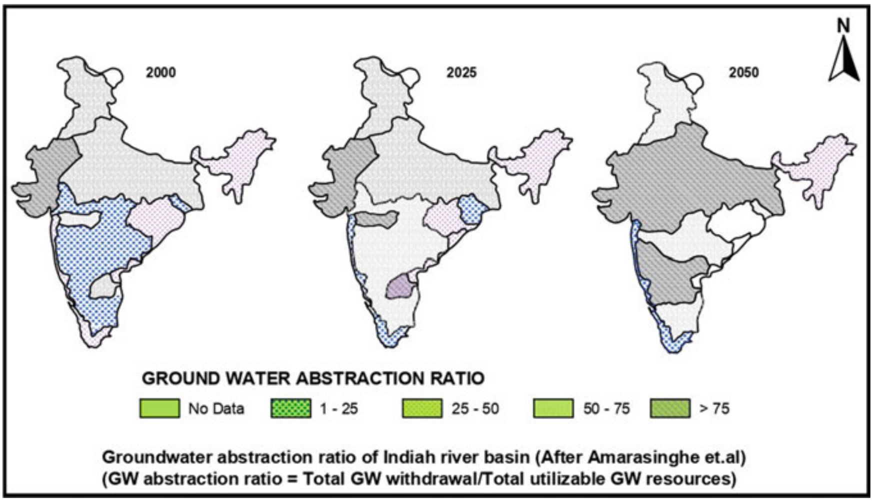

Fig. 21.2 Groundwater abstraction ratio of Indian River Basin (After Amarasinghe et al. 2016) (GW abstraction ratio = total GW withdrawals/total utilizable GW resources)

Siwalik sub-groups were laid down in the foredeep under fluvial and piedmont conditions. These sediments are coarse-grained close to Himalayas and become finer toward the craton and showed a typical coarsening upward cycle. During Upper Pleistocene, the foreland basin was subjected to upheaval due to continued subduction of Indian plate and the Siwalik was uplifted, deformed, and thrusted along the Main Boundary Thrust (MBT). This thrust gave rise to Ganga foredeep in which the Ganga alluvium has been laid down.

21.3.2 Geometric Configuration of the Multi-aquifer Systems

The alluvial plains of the Indo-Gangetic Basin (IGB) constituted 25% of the total land area of India and are composed of a thick pile of sediments belonging to the Tertiary and Quaternary ages. This vast and thick alluvial fill, exceeding 1000 m at places, constitutes the most potential and productive groundwater reservoir in India. Two distinct trends of groundwater flow direction are discernible. In the Indus basin, the elevation of water table ranges from less than 150 m *amsl* in the western part to more than 200 m *amsl* in the eastern part. The groundwater flow direction is SE to NW. In the Ganga basin, the elevation of water table ranges from about 200 m *amsl* in the western part to <20 m *amsl* in the eastern part. The general direction of groundwater flow is from NW to ESE.

The Indo-Gangetic basin is characterized by hugely productive multi-aquifer systems with long regional extensions. The deeper aquifers available in the basin provide substantial groundwater resources for further development. In the Indo-Ganga plain, wells constructed by the concerned Government organizations in the deeper aquifers have yielded within the range of 25–50 *lps* at economic drawdowns. A schematic diagram of the groundwater flow in different aquifer systems in the Indo-Gangetic basin is depicted in Fig. 21.5. The Tertiary and Quaternary sediments in the foreland of IGB overlie on different older litho units in different parts of the foredeep. The seismological study by Oil and Natural Gas Commission (ONGC) reveals that the basement topography has a number of highs and lows traversed by several faults, which have affected the deposition of Tertiary and Quaternary sediments (Sinha et al. 2005). Overall 2000–5000 m thick Siwalik (Tertiary) sediments of the foreland basin underlying the alluvial plain rest on a gentle northwardly sloping Pre-Tertiary

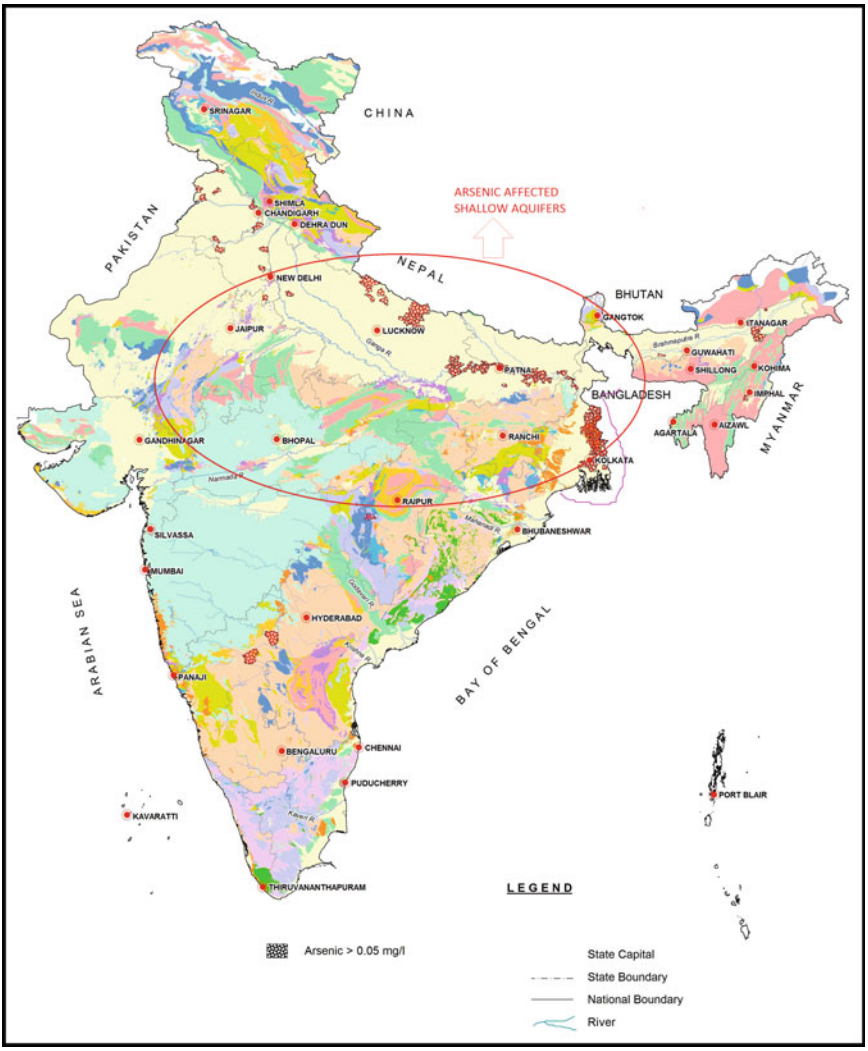

Fig. 21.3 Arsenic affected shallow aquifers in the IGB of India. *Source* CGWB

floor. The thickness of these sediments increases toward north, being maximum along the northern margin of the Himalayan foothills and minimum in the southern margin over the Vindhyans or Bundelkhand massif. Thick alluvium (590 m) and the underlying 2000–5000 m thick Siwalik formed a mammoth sequence of sedimentary deposits in the Indo-Gangetic basin.

As per Oil India Ltd., the evidences derived from the exploratory wells has conclusively established that the combined thickness of alluvium and Upper Siwalik ranges from 320 to 1500 m. This formation comprises potential aquifers with primary porosity. The prospects of suitable quality of groundwater are found only in the Alluvium of Upper Siwalik and up to certain pockets of the Middle Siwalik. The Lower Siwalik and lower parts of Middle Siwalik contain brackish/saline groundwater. The older formations are falling in the area of less groundwater development. The Gangetic alluvium deposited over the Siwalik sediments shows distinct lithological facies in different segments. In the northern part close to the Siwalik foothills, the alluvium is dominantly constituted of gravel and sand with subsidiary clays; while the inter-core area is

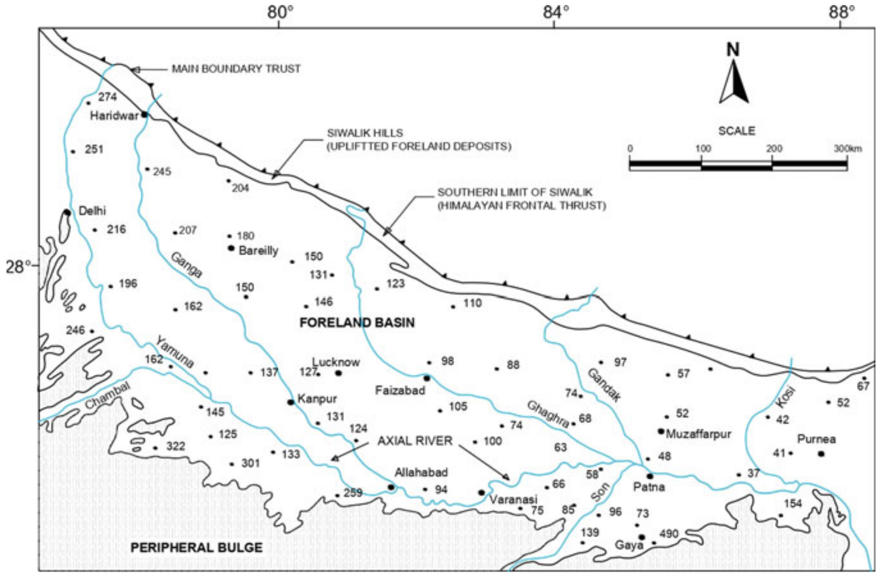

Fig. 21.4 The Ganga Plain highlighting Siwalik's point heights, slope patterns, and Foreland Basin (After Singh 1996)

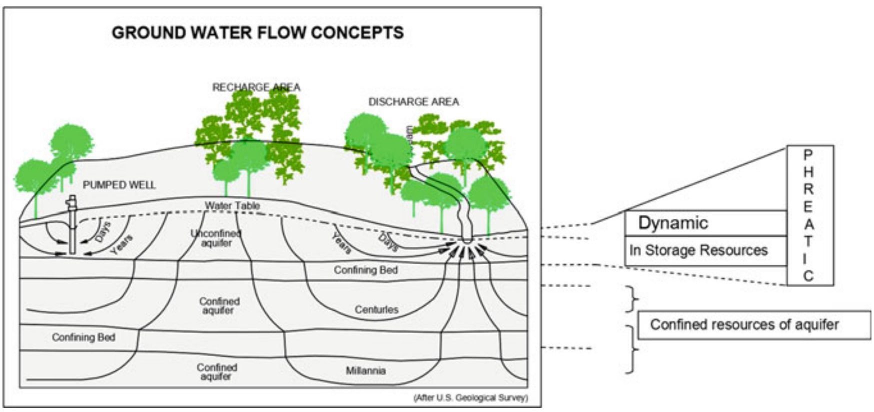

Fig. 21.5 Schematic diagram of groundwater flow system (after USGS)

enriched with clays. The Central Ganga Alluvial Plain is mainly characterized by clay, clay-kankar, and fine sand facies with occasional sand beds and sometimes comprises of gravels. The southern marginal alluvial plain shows coarse-grained sand, fine sand, and clay sequences.

21.3.3 Siwalik Aquifer System

The (I-G) alluvial plain and the underlying foreland basin are the part of (I-G) foredeep. The plain is ranging from Delhi-Aravalli ridge in the west to Rajmahal hills in the east. Its northern boundary is formed by the Siwalik Hills (Parkash et al. 1980), while the southern boundary is limited by the Bundelkhand-Vindhyan-Hazaribagh plateau. The (I-G) alluvial plain is a shallow asymmetrical depression underlain by the foreland basin having a gentle slope toward east. Northern part of the plain, adjacent to the Himalayan foothills, shows southerly and south-easterly slopes. Southern part of the plain is comparatively narrow and shows northerly to north-easterly slopes. The formation of plains is closely linked with Himalayan orogeny and the foreland basin is the resultant product of collision of Indian and Asian continental plates. Basement configuration indicates that the basin maintains slopes from west to east, and the maximum thickness of alluvium and Siwaliks is available in the Ganauli-Kadmaha section (Singh and Nambiar 1993). As studied by ONGC Ltd., in Puranpur depression, the thickness of Quaternary and Siwalik sediments varies from 1698 to 3068 m. The thickness of Quaternary and Siwalik sediments is more in Gandak depression than in Puranpur depression. A well-marked argillaceous bed is present in Tilhar and Matera areas in the Sarda depressions. Middlemiss (1900) proposed that Indo-Gangetic depression was a belt of subsidence, where the sinking of plains went on simultaneously with the rising of the mountains. It was the famous Swiss Geologist Edward Suess, who called it a foredeep of the Himalayas.

According to Rao (1973), the Indo-Gangetic depression is divided into five from east to west, i.e., (i) The Brahmaputra Basin in Assam; (ii) The Bengal Basin (Ganga-Brahmaputra) Basin in West Bengal and Bangladesh; (iii) The Ganga Basin in Uttar Pradesh and Bihar; (iv) The Punjab Basin in the Punjab, and (v) The Indus basin in Pakistan. Burrard (1915) advocated that the Indo-Gangetic trough was a great crustal crack or rift, perhaps as much as 30 km in-depth, which developed through a length of over 3200 km and got filled with alluvium. Seismic and gravity studies (Khattri 1987) suggest that the crustal thickness beneath the Indo-Gangetic plains is 28–45 km, including a 3 km top sedimentary layer. Regional continuity of freshwater aquifers and their thickening toward the north near foothills is very evident (Fig. 21.6).

21.3.4 Pleistocene and Flood Plain Deposits

Late Pleistocene is a period of severe climatic changes. Formation of different regional geomorphologic surfaces including active flood plain surfaces is related to the climatic cycles of Late Pleistocene-Holocene during 128 ka BP. These surfaces are depositional in nature and are overlain by the sediments with consecutive younger upward sequences. The Ganga plains are comprised of innumerable river networks, which have originated from parts of Himalayan Mountains, Peninsular craton, and alluvial plains formed in different periods in the late Pleistocene-Holocene. The sediments deposited in the IGB plains are originated from Himalayas undergo huge chemical weathering phenomenon resulting in the removal of Na, Ca, Sr, K, Mg and subsequent enrichment of As, Cr, Ni, and Th. In preferable hydro-chemical conditions, Smectite and Kaolinite are formed, which are partly eroded and transported to the delta region. During the Holocene period, deposition in the entranced river channels increased in response to the rising sea level (Singh 2007).

21.3.5 Geometry of Alluvial Aquifer Systems

The axis of the cusp runs in NW-SE direction passing through Saharanpur, Barielly, Sitapur, Lucknow, Basti, and Ambedkar Nagar in Uttar Pradesh, mid-central Bihar, and western portion of West Bengal states (Mathur 2003). In the states of Haryana and Punjab the basin is shallower than in Uttar Pradesh. The basin gradually becomes shallow across the central axis toward NE, where it merges with the foothills of Himalayas. The basin became comparatively shallow at the SW of the central axis, where it merges with Delhi Super Group, Bundelkhand, Vindhyans, Gondwana Super Group, and Chota Nagpur Plateau.

21.3.6 Thickness of Granular Zone in Unconfined Aquifer

The distribution of thickness of in-storage portion of unconfined aquifer in the alluvial area of the Indo-Gangetic basin is required to understand the static groundwater resources (CGWB 1997). The study on exploratory boreholes reveals that

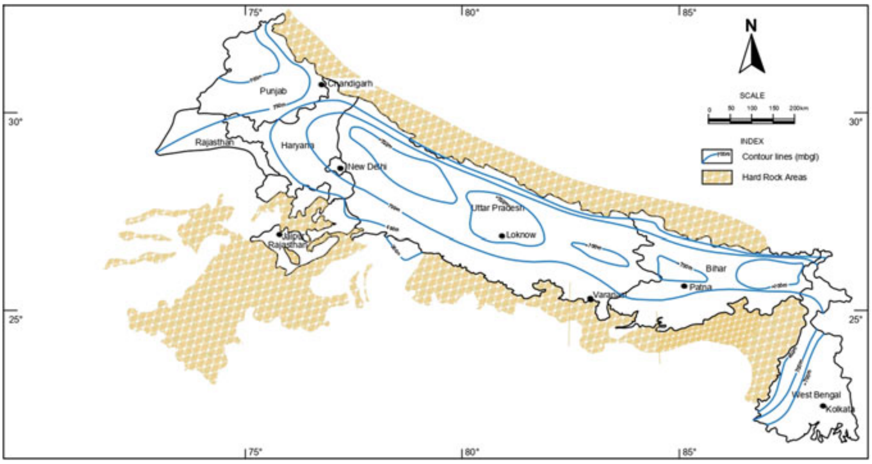

Fig. 21.6 Basin configuration map of IGB in India. *Source* CGWB

in the Indus basin the thickness of unconfined aquifer varies from less than 50 m to >100 m. The minimum thickness of the unconfined aquifer of about 50 m is observed in western part of Haryana, which increases gradually to 100 m toward northern part of the state and also in Punjab state. In the Ganga basin, central and eastern part of Uttar Pradesh is attributed to thickest aquifer material of 120 m under unconfined condition as compared to Western and North-Western part of Uttar Pradesh, where it is less than 100 m. In the state of Bihar, maximum thickness is 80 m in North-Eastern part of the state (Sinha et al. 2005). The thickness further decreases in West Bengal. The average thickness of aquifer in Bihar under unconfined conditions is about 100 m except in the regions forming basin boundary, where it is about 50 m. The state of Rajasthan indicates presence of prominent unconfined aquifer system all along the boundary with the states of Punjab, Haryana, and Uttar Pradesh and the thickness ranges between 60 and 100 m.

In the Indus basin, the cumulative thickness of granular zone ranges from 30 to 50 m in general in the states of Haryana and Punjab. However, it increases to more than 80 m in Punjab state in the bordering area of Pakistan. The cumulative thickness of granular zone in Rajasthan varies from 20 m to more than 50 m. In the Ganga basin, the central and eastern region of Uttar Pradesh., southern and eastern Bihar, northern and western parts of West Bengal State, and NE part of Rajasthan have maximum thickness of granular zones ranging between 40 and 60 m. The areas having cumulative thickness of more than 70 m of granular zone are found in eastern Bihar and western part of West Bengal. In the state of West Bengal the thickness of granular zone in the in-storage section reduces to less than 20 m in the southern part. A total of 421,112 km^2 is underlain by confined aquifers down to 450 m, in the basin.

21.3.7 Thickness of Granular Zone in the Confined Aquifer

The central region of the basin comprising the states of Uttar Pradesh, Punjab and Bihar have around 200 m thick granular material, which increases to more than 300 m at several places. The confined aquifer along the foothills of Himalayas in the state of Uttar Pradesh, Haryana, Punjab, and parts of Bihar also indicates the presence of about 100 m thick granular zone. The alluvial region of Uttar Pradesh., Bihar, Jharkhand, Haryana bordering Vindhyans, Bundelkhad, Gondwanas, and Delhi Group of formation has minimum thickness (<50 m) of granular material in the confined aquifer down to 450 m. In the state of West Bengal, maximum thickness of granular material encountered within 450 m in the confined aquifer ranges between 100 and 150 m. It is pertinent to mention here that confined aquifer does not exist in the Rajasthan part of the Indo-Gangetic basin. The distribution of cumulative thickness of granular zones occurring below the confining layer down to depth of 700 m bgl in the confined aquifer in the Indo-Gangetic basin, which needs prime attention. A total of 332,524 km^2. area is underlain by confined aquifers down to 700 m in the basin. It is observed that the thickness of granular zone is in conformity with the configuration of basin. It is of the order of 300 m to 350 m along the central axis in central and eastern parts of Uttar Pradesh (Pathak et al. 1985), 500 m in central Bihar, 250 m in Haryana, and 300 m in Punjab.

21.4 Groundwater Resources Assessment and Data Analysis

21.4.1 Water Resources of Unconfined Aquifer

The study reveals that the total replenishable groundwater resources all over the alluvial plain are 196.22 Billion Cubic Meter (BCM)/yr, which include the recharge of 144.55 BCM/yr and 51.664 BCM/yr during monsoon and non-monsoon seasons, respectively. The annual groundwater draft includes both the irrigation draft coupled with the domestic and industrial uses of groundwater. Thus, the total annual groundwater draft of the study area is 144.77 BCM/yr (Table 21.1). Among nine states and one Union Territory (U.T.) in the study area, the Uttar Pradesh state holds maximum amount of replenishable groundwater resources (76.34 BCM) and the draft (52.76 BCM), whereas the Delhi U.T. holds the least amount of replenishable groundwater resources (0.34 BCM) and the draft (0.39 BCM). Natural discharge during non-monsoon season in the study area ranges from 0.03 BCM to 4.75 BCM. The study area witnesses the stage of groundwater development within the range of 23% (Minimum) in Jharkhand state and 149% (Maximum) in Punjab state. The brackish/saline groundwater resources are available within the states of Haryana, Punjab, Rajasthan, Uttar Pradesh, and West Bengal. Net annual groundwater availability of the study area maintains the range between 0.31BCM and 71.58 BCM.

21.4.2 Groundwater Development Strategy from Confined and Unconfined Aquifers

Groundwater resources are considered by their location, their occurrence over time, their size, proportions, conditions of accessibility, the effort required to mobilize them, and therefore and their cost. All these are to be considered for planning and development. Groundwater, in Indo-Gangetic basin, occurs both under unconfined and confined conditions. The disposition of the aquifer varies from one location to another location (in space) and can be well understood using the subsurface configuration of aquifers which can be obtained from groundwater exploration data. The development plan is a function of water availability, groundwater draft, and economic viability. A comprehensive developmental plan requires the assessment of development-worthy groundwater resources, draft per tube well, and the cost to develop this resource (Prasad 1993). This helps in determining the number of tubewells feasible for construction in a particular aquifer and funds required to construct these tubewells.

Groundwater resources, in an unconfined aquifer, are classified into two categories namely the dynamic and the in-storage resources. The groundwater resource which gets replenished annually forms the dynamic resource, whereas the resource occurring below the average fluctuation zone forms the in-storage/static recourses. The dynamic groundwater resource is assessed for each district of all the states encompassed by the Indo-Gangetic basin. Block/sub-basin may be considered as the assessment unit.

Table 21.1 State-wise Groundwater Resources Availability, Utilization (in BCM), and Stage of Development (%)

S. No.	States / Union Territories (U.T.)	Annual replenishable ground water resources					Natural Discharge during non-monsoon season	Net annual ground water availability	Annual ground water draft			Projected demand for domestic and industrial uses up to 2025	Ground water availability for future irrigation use	Stage of ground water development (%)
		Monsoon season		Non-monsoon Season		Total			Irriga tion	Domestic and industrial uses	Total			
		Recharge from rainfall	Recharge from other sources	Recharge from rainfall	Recharge from other sources									
1	Bihar	20.66	3.48	3.36	3.81	31.31	2.82	28.49	10.36	2.37	12.73	0.6	17.52	45
2	Delhi U.T	0.09	0.02	0.014	0.22	0.34	0.03	0.31	0.14	0.25	0.39	0.25	0.02	127
3	Haryana	3.62	3.1	1.03	3.6	11.36	1.06	10.3	13.32	0.6	13.92	0.56	−3.58	135
4	Himachal Pradesh	0.4	0.02	0.11	0.03	0.56	0.03	0.53	0.16	0.11	0.27	0.07	0.3	51
5	Jharkhand	5.61	0.06	0.73	0.16	6.56	0.57	5.99	0.63	0.72	1.35	0.17	5.19	23
6	Punjab	5.75	13.21	1.32	5.64	25.91	2.52	23.39	34.05	0.77	34.81	0.97	−11.63	149
7	Rajasthan	9.06	0.69	0.27	2.49	12.51	1.26	11.26	13.79	1.92	15.71	2.32	0.9	140
8	Uttar Pradesh	41.97	11.52	4.6	18.25	76.34	4.75	71.58	48.35	4.41	52.76	6.44	19.01	74
9	Uttarakhand	1.1	0.22	0.24	0.43	2	0.03	1.97	0.84	0.15	0.99	0.3	0.82	50
10	West Bengal	18.71	5.26	1.51	3.85	29.33	2.77	26.56	10.84	1	11.84	1.53	14.19	45
	Total (09 State & 01 U.T.)	106.97	37.58	13.184	38.48	196.22	15.84	180.38	132.48	12.3	144.77	13.21	42.74	Ranges from 23 to 149%

Source Central Ground Water Board (CGWB), India

The groundwater resources of confined aquifers have been built up over considerably long period of time and are annually not replenishable; hence they have been considered as finite in the present context. Accordingly, the development plan is based on draft from tube wells for their life period considered to be 25 years. Account of the number of wells in each state shows that Uttar Pradesh ranks first in the case of wells numbers in confined aquifers and Uttarakhand ranks last. This might be the reason for the high and low draft of groundwater in Uttar Pradesh and Uttarakhand, respectively.

The Net Ground Water Availability for future irrigation in the entire Indo-Gangetic basin, is assessed to be 180.38 BCM. To prepare the developmental plan the net available resources were divided by the unit draft/annum, of a representative tube well tapping the dynamic zone of the unconfined aquifer. This gives the number of additional tube wells, which are required to be constructed to develop the available dynamic resources. The numbers of tube wells were multiplied by the unit cost of tube well construction. The unit cost is given due to considerations of the nature of aquifer material, depth, and local factors. As per GEC 2015, state-wise groundwater resources, status of utilization, and stage of groundwater development in the IGB are depicted in Table 21.1.

21.5 Conclusion

The unconfined aquifer is covering an area of 466,007 km^2, having holding substantial groundwater resources for future irrigation development. Groundwater resources in the states of Uttarakhand, U.P., Bihar, Jharkhand, and West Bengal are available for future irrigation development. As per GEC Methodology, 2015, Net Ground Water Availability for future use in the I-G basin is maximum in the Uttar Pradesh (U.P.) state (71.58 BCM/yr.) and minimum in the Delhi U.T. (0.31 BCM/yr.). Comparative studies of two consecutive estimations indicate that total groundwater extraction in the year 2017 is 145 BCM, which was 117 BCM/yr. in the year 2009. At present stage of groundwater extraction in the I-G basin ranges from 23% (Jharkhand state) to 149% (Punjab state). Groundwater availability for future irrigation use in the year 2017 was 42.74 BCM/yr, which was 57.68 BCM/yr in the year 2009. However, it is worthwhile to point out that development potential of aquifers down to different depths should not be separately calculated, because it is ultimately one unified system on regional basis and any development carried out in the topmost aquifer will have its bearing on underlying aquifers. Demand and supply-side management to be done in a judicious manner to maintain long-term sustainable yield from the IGB aquifer systems. Conjunctive use of surface water and groundwater along with water conservation and location-specific interventions would be beneficial impact on the basin. To minimize the wastage of water in the irrigation sector, the viable options would be the precision agriculture which includes drip and sprinkler irrigation methods.

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