Chapter 2
Groundwater Resources of India: Potential, Challenges and Management

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1 Introduction

Recent research has revealed that two-thirds of the world's population currently lives in areas that experience water scarcity for at least 1 month a year. Noteworthy is that about 50% of the people facing this level of water scarcity live in China and India (UN-Water 2017). Though India receives a copious annual precipitation of around 4000 × 10^9 m^3, only around one fourth (1123 × 10^9 m^3) of it is utilizable. A country is considered to be under regular water stress when the renewable water supplies drop below 1700 m^3 per capita per year and it faces chronic water scarcity when the water supplies drop below 1000 m^3 per capita per year (Falkenmark and Widstrand 1992). The per capita average water availability in India in the year 2001 was 1816 m^3 which is likely to reduce to 1140 m^3 in 2050 (MoWR 2015). In the recent past, major share of the increased demand for water has been met from aquifers and groundwater has steadily emerged as the backbone of India's agriculture and drinking water security (Vijay Shankar et al. 2011). Today, contribution of groundwater is ~62% in irrigation, ~85% in rural water supply and ~45% in urban water consumption. High dependence on groundwater resources has led to stressed conditions in various parts of the country. This calls for holistic understanding of the aquifer systems and management of this precious natural resource in a sustainable manner.

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2 Hydrogeological Setup

Hydrogeological setup is the primary control of occurrence and movement of groundwater. The groundwater resources map of Asia brought out by the World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP; UNESCO 2008) shows that India holds more potential aquifer systems in comparison to most of her neighbours (Fig. 2.1). In this map, except the Indo-Ganga-Bramhaputra plains and tracts along large rivers, major part of India has been designated as areas with 'complex hydrogeological structure' (UNESCO 2008). Taylor (1959), based on geology and terrains, delineated eight broad groundwater provinces. This classification of groundwater provinces of India has been in wide use in literature (Karanth 2003). The National Atlas on Aquifer Systems of India (CGWB 2012a) has adopted a two-tier classification of aquifer systems of India. The aquifers are classified into 14 principal aquifer systems, which in turn have been sub-divided into 42 major aquifer systems. Kulkarni et al. (2015) have divided the country into six hydrogeological settings (aquifer typology).

The geological units in India can be grouped into two broad categories based on groundwater storage and transmissive properties: (i) soft rock and (ii) hard rock. The soft rocks characterized by the predominance of primary porosity can further be divided into unconsolidated sediments and semi-consolidated rocks. The hard rock formations, characterized by predominance of secondary porosity like fractures and joints can be broadly grouped into Precambrian sedimentaries, basaltic aquifers,

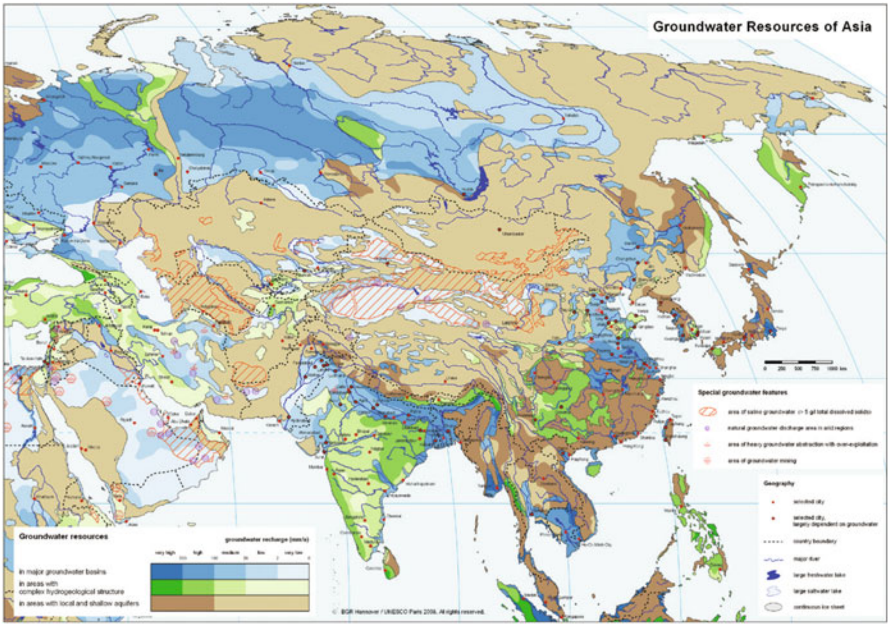

Fig. 2.1 Groundwater resources of Asia. (*Source*: UNESCO 2008)

crystalline aquifers and the carbonate aquifers. Aquifers in the hilly areas (Himalayan Terrain) are complex and discontinuous. Similarly, the aquifers and the groundwater dynamics in the islands are unique and are described separately. Geographical distribution of various hydrogeologic units as described above is shown in Fig. 2.2.

2.1 Hard Rock Aquifers

The hard rock aquifers, as a group, cover major part of the geographical area of the country, of which the crystalline aquifers are the most predominant type. Most

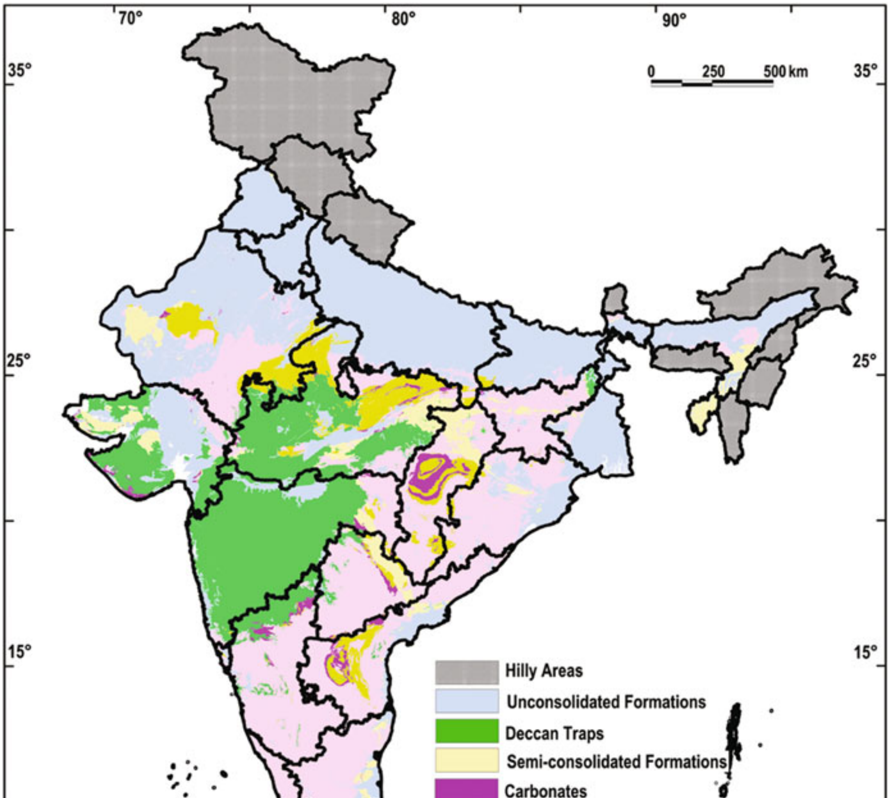

Fig. 2.2 Major hydrogeological units in India. (Adapted from the Aquifer Atlas of India; CGWB, 2012)

common rock types categorized under crystalline aquifers are granites, gneisses, charnockites, khondalites, quartzites, schist and associated phyllite, slate, etc. These rocks possess negligible primary porosity but are rendered porous and permeable due to weathering and due to the presence of fractures and joints. The crystalline aquifers cover major parts of the States of Andhra Pradesh, Chhattisgarh, Karnataka, Kerala, Odisha, Tamilnadu, Telangana and Jharkhand. The upper weathered part and the fractured zone below form the aquifers. The fracture zones are connected along some alignments (lineaments) and when they are well-connected with the top weathered zone form potential aquifers (Saha et al. 2013). Potential aquifers are restricted mostly up to a depth of 150 m. Transmissivity of these aquifers remain mostly within 100 m^2/day, though occasional values up to 600 m^2/day has also been reported. Though of limited potential, these aquifers occur widely and act as the principal source of freshwater in the country.

The Precambrian sedimentaries are encountered mostly in parts of Andhra Pradesh, Chhattisgarh, Madhya Pradesh and Rajasthan. Major rock formations include sandstones and shale. Usually the Precambrian sandstones are highly silicified and the shales are compact (Ray et al. 2017). Both sandstones and shale have very limited aquifer potential with specific yield value of around 0.0038 (Ray et al. 2014).

Basaltic aquifers occupy most part of Maharashtra and large geographical areas in Gujarat and Madhya Pradesh. They comprise multiple flows (traps). Each flow is marked by a potential vescicular zone at the top and a massive rock unit at the bottom (Saha and Agrawal 2006). The weathered part of the top flow and the vescicular zone of the successive flows below and the intertrappeans form aquifers. The weathered zone mostly remains within 15 m though in some parts of Karnataka and Gujarat 40 m thick weathered zones have also been reported (CGWB 2012a). Transmissivity of these aquifers remain mostly within 70 m^2/day. Patches of basaltic aquifers are also reported from other parts of India like Chhattisgarh, Rajmahal Traps in Eastern parts of Jharkhand etc.

Carbonates ranging in age from Precambrian (as in Chhattisgarh State) to Tertiary (as in Rajasthan) make potential aquifers owing to various degrees of karstification. Most prominent carbonate aquifers are in the central part of Chhattisgarh. These carbonate units belong to the Precambrian Chhattisgarh Group of rocks (Mukherjee et al. 2014). Dar et al. (2014) provide a review of the karst (carbonate) aquifers in India. Potential water bearing zones in these carbonate aquifers are mostly restricted to 80 m below ground level. Usually, degree of karstification and consequent groundwater potential decrease with depth. Rainfall Infiltration factor and specific yield of the carbonate aquifers in Chhattisgarh has been estimated to be 4.5% (Ray et al. 2017) and 3.7% (Ray et al. 2014) respectively.

2.2 *Soft Rock Aquifers*

Soft rock aquifers can be further subdivided into unconsolidated sediments and semi-consolidated sedimentaries. The unconsolidated sediments in turn can be grouped into three broad categories: (i) alluvial deposits in Indo-Ganga-Bramhaputra Plains and along tracts of major rives, (ii) coastal deposits, most prominent along the east-coast, and (iii) aeolian deposits in the northwestern part. The Indo-Ganga-Brahmaputra plains hold one of the most potential soft rock aquifers in the world. The unconfined aquifers occurring at the top sometimes extend down to 125 m. Deeper aquifers are mostly leaky-confined/confined (Saha et al. 2007; Saha et al. 2011; Saha et al. 2013). The unconfined aquifers generally show storage coefficients between 5% and 25% (Saha et al. 2009). Transmissivity values vary widely from 1000 to 5000 m^2/day (CGWB 2012a). Transmissivity values of deeper aquifers may go up to 12,000 m^2/day (Saha et al. 2010). These aquifers may yield as high as 70 litres per second. The potential of alluvial aquifers along the peninsular rivers are rather moderate with yield up to 14 litres per second. But the alluvial deposits (~100 m thick) of Narmada, Tapi, Purna basins may yield up to 28 litres per second. The alluvial sequences in deltas of major rivers on the eastern coast and in Gujarat estuarine tracts have their hydrogeological potential limited by salinity hazards.

The aeolian deposits occurring in West Rajasthan, Gujarat, Haryana, Delhi and Punjab are well sorted and permeable and have moderate to high yield potentials. However, natural recharge is poor because of scanty rainfall in the area and water table is deep.

The semi-consolidated formations mainly comprise shales, sandstones and limestones. The sedimentary deposits belonging to Gondwana and Tertiary formations are included under this category. The sandstones form potential aquifers locally, particularly in Peninsular India, but at places they have only moderate potential. Under favourable situations, these sediments give rise to artesian conditions as in parts of Godavari Valley, Cambay Basin and parts of West Coast, Puducherry, Neyveli in Tamil Nadu and Tertiary belt in Tripura. Potential aquifers particularly those belonging to Gondwanas and Tertiaries have transmissivity values from 100 to 2300 m^2/day (CGWB 2012a).

2.3 *Hills and Islands*

Hydrogeological units in the Himalayan terrain (Fig. 2.2) are complex and have not yet been explored properly. The aquifers are discontinuous. Information about extent of the aquifers, their hydraulic properties, recharge areas, recharge mechanism, pathways of recharge etc. are scanty. The Himalayas occupy nearly 500,000 km^2 covering major parts of the States of Jammu and Kashmir, Uttarakhand, Himachal

Pradesh, Sikkim and the northeastern States. Valleys within the hilly terrain are the areas with significant groundwater potential. Because of highly undulating terrain and structurally complex nature owing to tectonic disturbances, groundwater often oozes out in the form of springs. These springs form potential sources of freshwater in this terrain.

Islands have unique hydrogeological characteristics, where fresh groundwater floats as a lens over saline water within the aquifers. Fresh groundwater lenses of small islands, in particular, are more vulnerable to external factors than continental coastal aquifers, and require additional attention (White and Falkland 2010; Ketabchi and Ataie-Ashtiani 2015). Two major islands in India are the Andaman and Nicobar Islands and the Lakshadweep Islands. Weathered and fractured ophiolites, calcareous marl and shell-coralline limestone are the major water baring formations in the Andaman and Nicobar Islands (CGWB 2012b). Coral sand and coral limestone are the main water bearing formations in Lakshadweep Islands (Najeeb and Vinaychandran 2011). In addition to the above two groups of islands (Archipelago), groundwater also form the major source of fresh water in the islands in other parts of India such as those in Andhra Pradesh, Assam, Daman and Diu, Goa, Gujarat, Karnataka, Kerala, Maharashtra, Odisha, Puducherry and West Bengal.

3 Groundwater Level Scenario

Central Ground Water Board (CGWB) periodically monitors groundwater levels through a network of 20,000 observation wells spread all over the country. Measurements of water levels are taken four times a year during the months of January, May, August and November. Besides this, the State Ground Water departments monitor approximately 60,000 wells. The monitoring wells include open dug wells as well as purpose-built piezometers. Detailed information regarding water level measurements done by CGWB is available on website (www.cgwb.gov.in) and its geoportal (www.india-wris.gov.in). Discussion on groundwater levels as presented here are based on water levels of the phreatic aquifers collected and archived by the Central Ground Water Board (CGWB 2016).

In general, annual deepest water levels are recorded during the month of May (Pre-monsoon) and the shallowest in August (Monsoon). As per the analysis of water levels for the year 2015, while nearly 30% of the wells show water levels shallower than 5 m below ground level (bgl) during the pre-monsoon period, percentage of such wells during monsoon period is as high as 60% (Fig. 2.3). Only less than 10% of the wells show water levels above 20 m bgl both during premonsoon as well as monsoon period. Spatial variation of water levels over the country during premonsoon period (May, 2015) is shown in Fig. 2.4 and that during monsoon period (August, 2015) is shown in Fig. 2.5.

During monsoon period (August), in major part of the country, water levels range between 5 and 10 m bgl. Very shallow water levels (<2 m bgl) are observed locally,

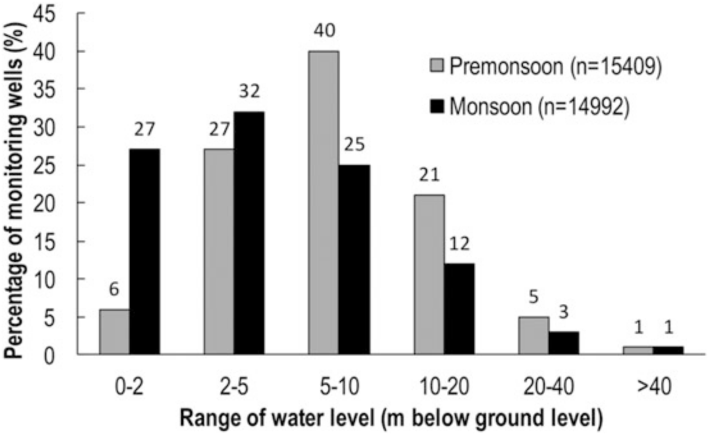

Fig. 2.3 Comparison of instances of water levels in different ranges during pre-monsoon and monsoon periods

in the states of Assam, Andhra Pradesh, Himachal Pradesh, and Tamil Nadu. The depth to water level generally varies from 2 to 5 m bgl in almost whole of Assam, coastal Tamil Nadu and in parts of Maharashtra, Andhra Pradesh, Uttar Pradesh, Bihar, Chhattisgarh, Odisha etc. In the western parts of the country, deeper water level is recorded in the depth range of 20–40 m bgl and more than 40 m bgl. In parts of Delhi and a major part of Rajasthan, water levels of more than 40 m bgl are recorded. Spatial pattern of water level variations over the country during the monsoon period is comparable to that in the premonsoon period albeit with shallower water levels (Figs 2.4 and 2.5).

Water levels show long-term (decadal) falling trends in many parts of the country. Areas, where falling trend is recorded during either pre-monsoon or post-monsoon period are shown in Fig. 2.6. Most of the areas with falling trends are in the States of Rajasthan, Punjab, Haryana, Delhi, Karnataka and Tamilnadu (Fig. 2.6).

4 Groundwater Resource Availability

Available groundwater resources can be defined as the volume of annual groundwater recharge from all sources that is available for use after taking into account the natural discharges that goes out from the aquifers (MoWR 2009). Rainfall is the major source of recharge, other sources being return flow from irrigation, seepage from surface water bodies, transboundary flows etc. While there have been many attempts to estimate the recharge at local and regional scales (Rangarajan and Athavale 2000), the country level groundwater assessments are done by CGWB in association with the State groundwater departments (CGWB 2014a; Chatterjee and Purohit 2009).

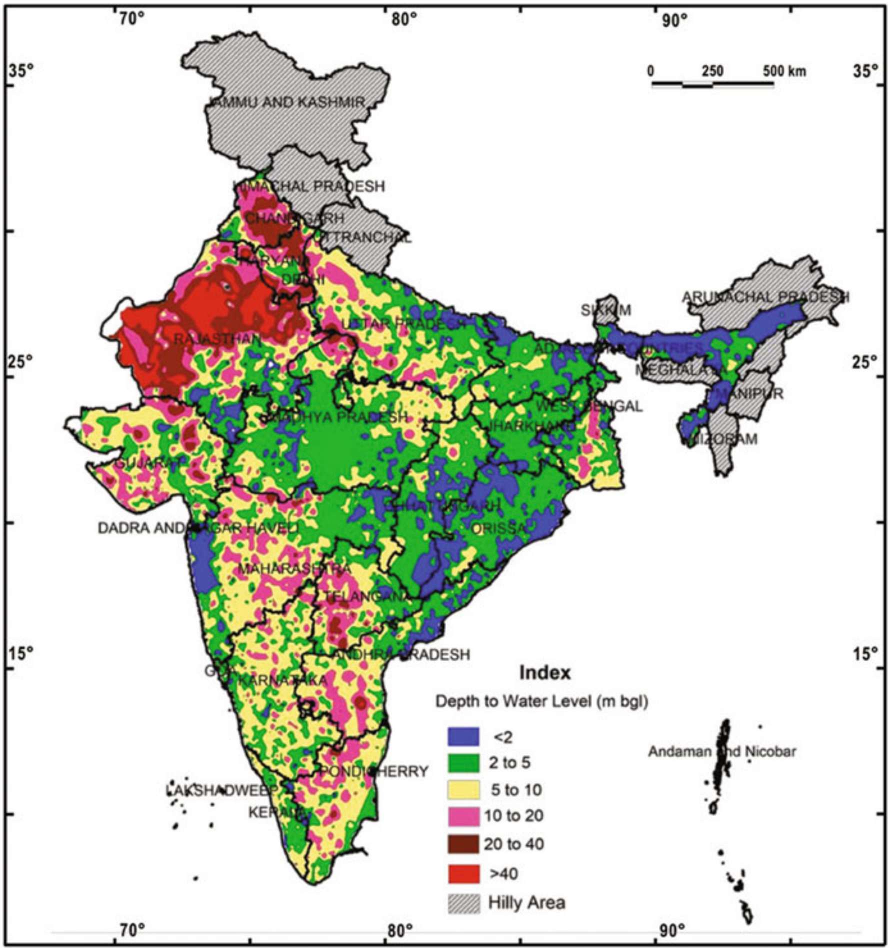

Fig. 2.4 Pre-monsoon (May, 2015) water levels over India

Groundwater resource assessment for the year 2011 (CGWB 2014a) records that total estimated annual availability of groundwater resources of the phreatic aquifers in the country is 398×10^9 m^3 of which recharge from rainfall accounts for nearly 70% and other sources contribute nearly 30%. Annual available resources in depth terms (mm) are shown in Fig. 2.7. Availability is much higher in the Indo-Ganga-Bramhaputra plains (>200 mm) in comparison to the peninsular part (mostly 100–200 mm). Annual availability is very poor (<50 mm) in almost entire Rajasthan, which receives scanty rainfall. Lower availability (<50 mm) as shown in parts of Gujarat is because it is the Rann area, where groundwater is mostly saline. Similarly, in south-eastern part of West Bengal also availability has been shown as <50 mm as in this part fresh water availability in the phreatic aquifer is poor and deeper aquifers are the principal sources of fresh groundwater.

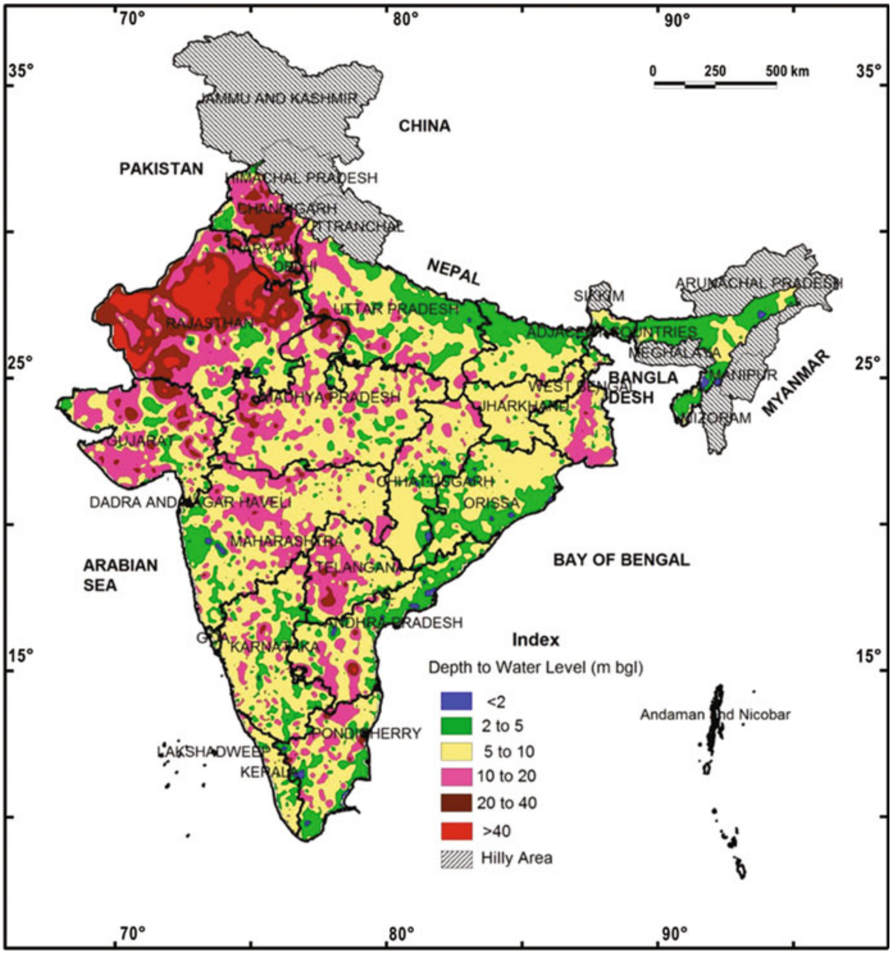

Fig. 2.5 Water levels during monsoon period (August, 2015)

5 Groundwater Extraction, Stage of Development and Categorisation

As per the estimates of the Government of India (CGWB 2014a), annual groundwater extraction (draft) in the country is 245×10^9 m^3, of which about 90% (222×10^9 m^3) is extracted for irrigation purposes. Remaining extraction of less than 10% (23×10^9 m^3) is for domestic and industrial purposes. Groundwater draft per unit area is much higher in the States of Punjab, Haryana, Uttar Pradesh and West Bengal in comparison to the other parts of the country (Fig. 2.8) as groundwater-based irrigation is intense in these areas. Draft per unit area is the lowest in Rajasthan commensurate with poor availability.

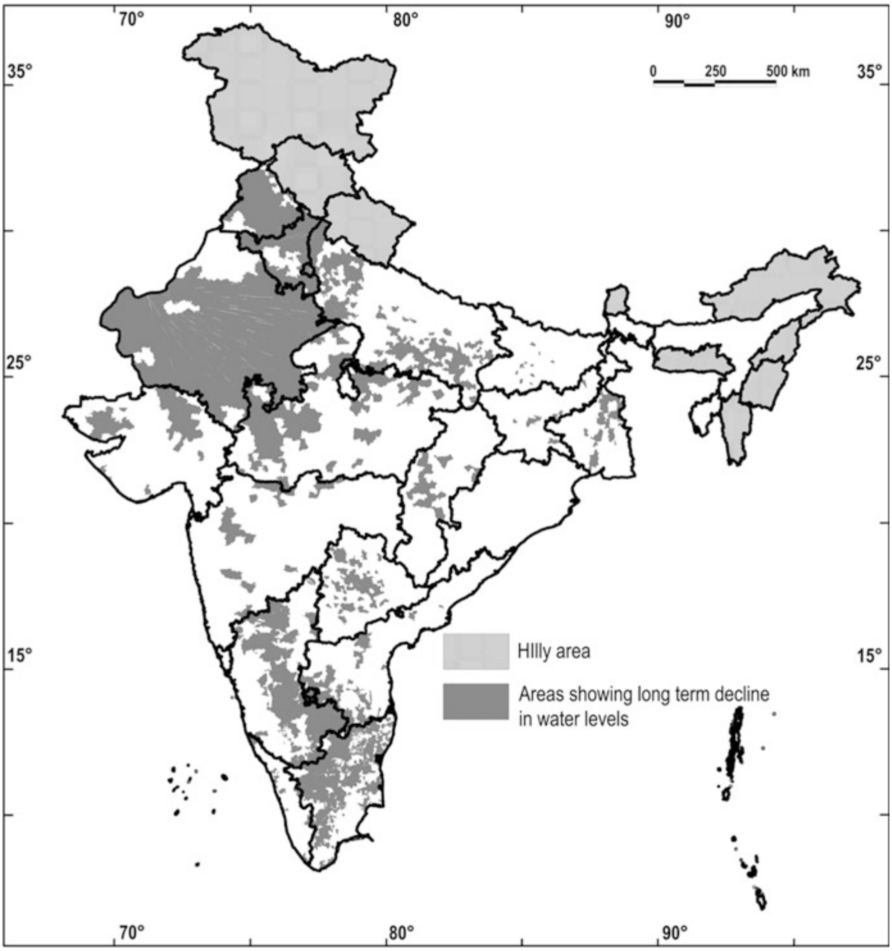

Fig. 2.6 Areas showing long-term decline in water levels during either of the one or both pre-monsoon and post-monsoon periods. (Adapted from CGWB, 2014)

'Stage of groundwater development' is a measure of extent of use of groundwater relative to annual availability (Eq. 2.1; MoWR 2009).

$$\text{Stage of Development} = \frac{\text{Annual Groundwater Draft}}{\text{Annual Available Resources}} \times 100 \tag{2.1}$$

A stage of development of more than 100% means that annual groundwater extraction in the concerned area is more than annual groundwater availability. Stage of development for the country as a whole is 61% (CGWB 2014a), though there is wide variation over the country (Fig. 2.9). Out of 6607 assessment units (CGWB 2014a), those with more than 100% stage of development are mostly concentrated in the States of Rajasthan, Haryana, Punjab, Tamilnadu, Delhi and

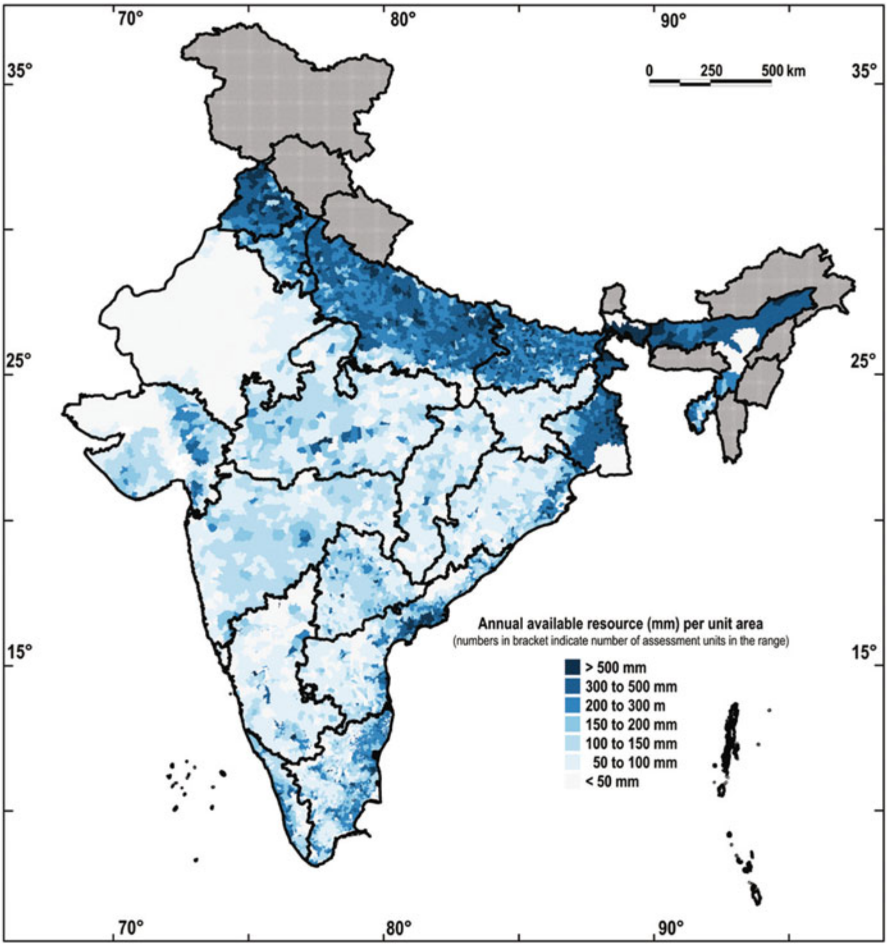

Fig. 2.7 Annual available groundwater resources in India. (Adapted from CGWB, 2014)

Karnataka (Fig. 2.10). Stage of groundwater development is low (<30%) mostly in the eastern part of the country covering parts of Bihar, Jharkhand, Chhattisgarh, West Bengal, Assam and eastern parts of Maharashtra and Madhya Pradesh.

For prioritization of areas for groundwater management, the assessment units (*firka* in Tamilnadu, *mandal* in Andhra Pradesh, *taluka* in Karnataka and blocks in most other states) have been grouped into four categories: 'over-exploited', 'critical', 'semi-critical' and 'safe' (CGWB 2014a). The categorisation is based on stages of groundwater development and long-term water level trends (MoWR 2009). Groundwater extraction in the overexploited units exceeds annual recharge and the water levels show falling trends. In critical units, extraction is more than 90% of the annual availability and in 'semi-critical' units extraction is more than 70% of the annual available resources. While immediate management interventions are recommended

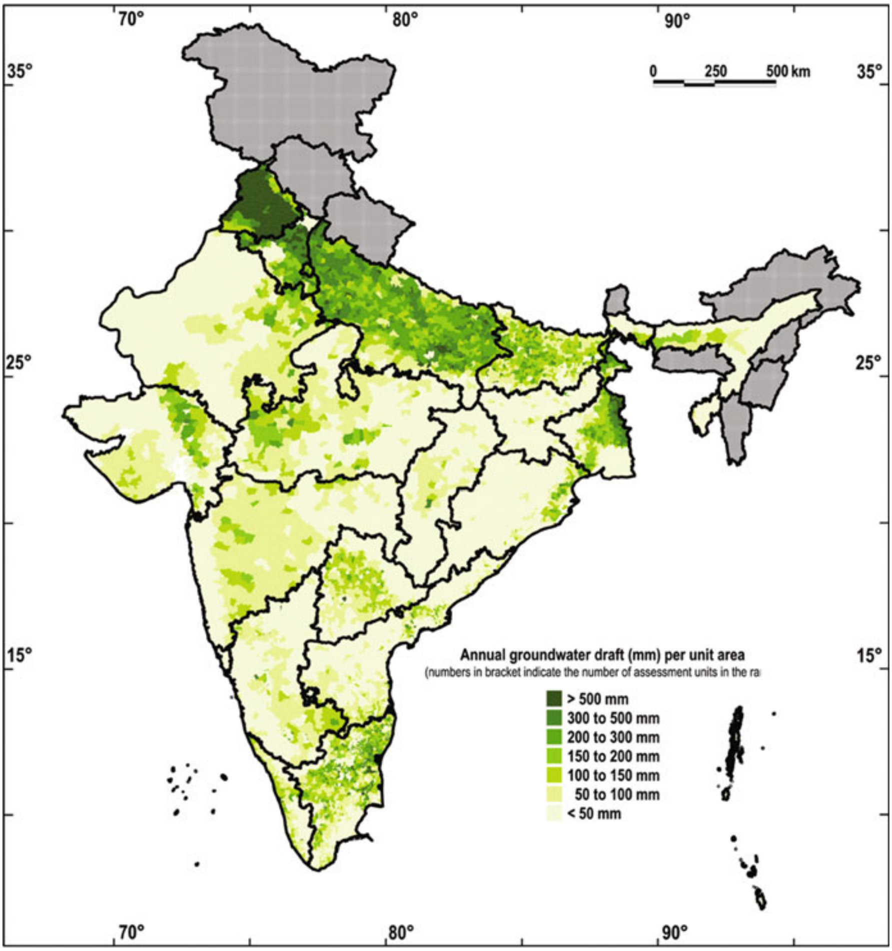

Fig. 2.8 Annual groundwater extraction (draft) in depth terms (mm)

for 'over-exploited' and 'critical' blocks, caution should be exercised in 'semi-critical units'. Out of 6607 numbers of assessed administrative units, 1071 are 'over-exploited', 217 are 'critical', 697 are 'semi-critical' and 4530 units are 'safe'. The remaining 92 assessment units are classified as 'saline' as major part of the phreatic aquifers in these units is saline (Fig. 2.10). Over-exploited blocks are concentrated in the north-western, western and southern Peninsular part of the country. Number of 'over-exploited' and 'critical' administrative units are significantly higher (more than 15% of the total assessed units) in Delhi, Haryana, Karnataka, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh and also in the Union Territories of Daman & Diu and Puducherry.

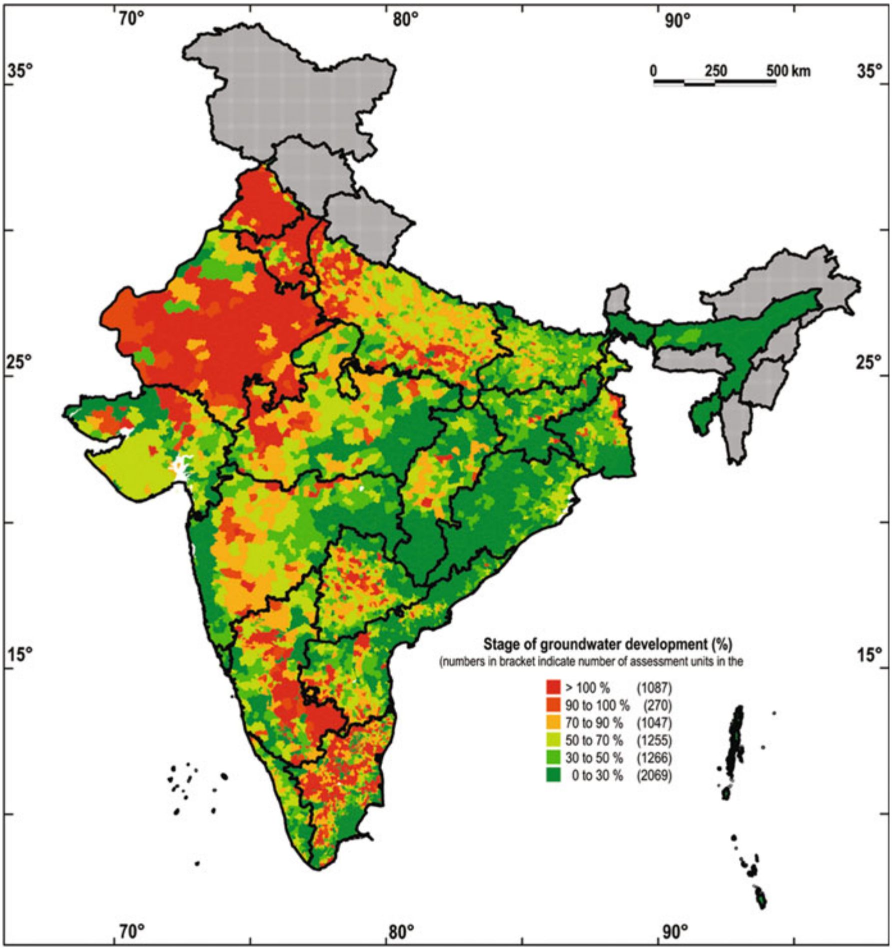

Fig. 2.9 Assessment unit wise stage of groundwater development (Adapted from CGWB, 2014)

6 Groundwater Contamination

Groundwater contamination, both from geogenic and anthropogenic sources, are reported from various parts of the country. Geogenic contamination, particularly that caused by high fluoride and high arsenic is widely reported. Besides this, salinity and high iron, though they are not as acute health hazard as arsenic and fluoride, have been reported from various parts. Anthropogenic contamination on the other hand is originated from industrial effluents, untreated sewage, leachates from landfills etc. The anthropogenic contamination is localized in geographical extent. The Integrated Management Information System (www.indiawater.gov.in) of the Ministry of drinking water and sanitation provide habitation wise status of different contaminants in drinking water (in most of the cases it is groundwater). CGWB has compiled the

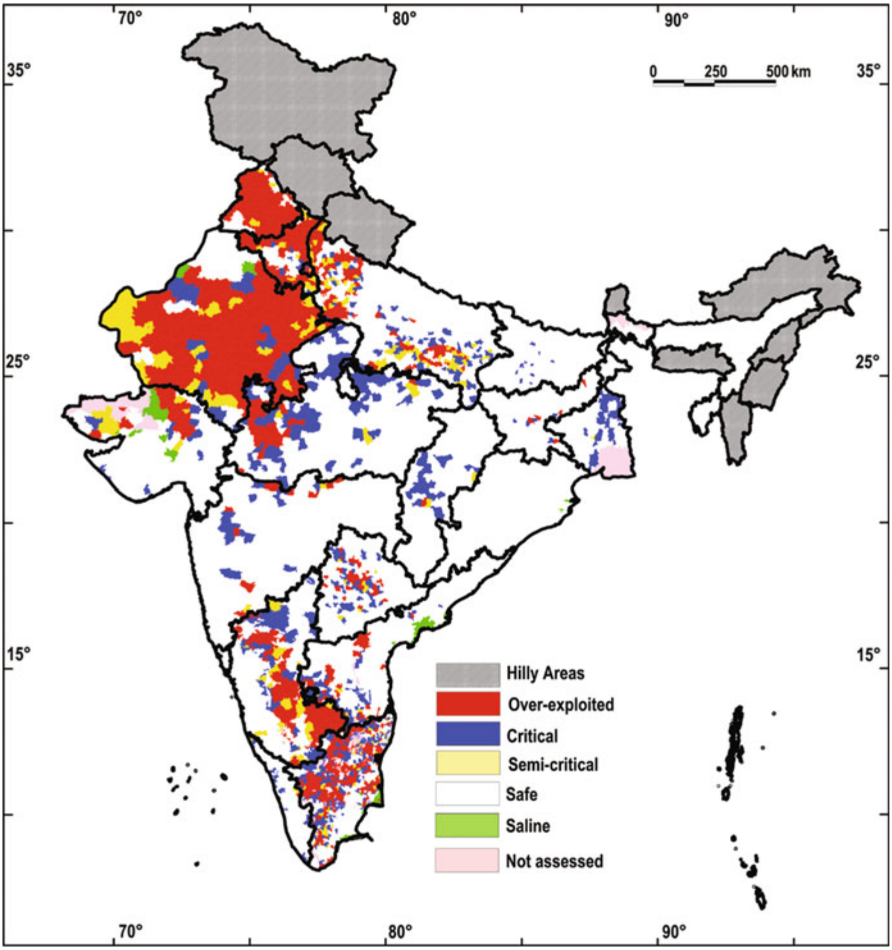

Fig. 2.10 Categorisation of assessment units as per groundwater resource assessments done by CGWB in association with State Ground Water Departments

contamination of groundwater in two documents (CGWB 2010, 2014b), which provide detailed account of groundwater quality in India. A summary of constituent wise maximum permissible limits in drinking water (Bureau of Indian Standard: IS 10500:2012) and States from where they were reported is provided in Table 2.1.

High concentration (>1.5 mg/L) of fluoride in groundwater is widely prevalent across the length and breadth of the country. However, it is more prevalent in the states of Andhra Pradesh, Tamil Nadu, Uttar Pradesh, Gujarat and Rajasthan, where 50–100% of the districts have drinking water sources containing excess level of fluoride. As per an estimate (FRRDF 1999) about 66 million people in India are consuming water with fluoride level beyond the permissible limit.

Table 2.1 Permissible limits in drinking water and State-wise instances of occurrence of fluoride (F), arsenic (As), salinity, iron (Fe) and nitrate (NO_3)

Constituent	Maximum Permissible Limit in Drinking Water (BIS 2012, 2015)	Number of States	States from where instances of contamination have been reported
Fluoride	1.5 mg/L	20	Andhra Pradesh, Assam, Bihar, Chhattisgarh, Delhi, Gujarat, Haryana, Jammu and Kashmir, Jharkhand, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Odisha, Punjab, Rajasthan, Tamilnadu, Telangana, Uttar Pradesh, West Bengal
Arsenic	0.01 mg/L	21	Andhra Pradesh, Assam, Bihar, Chhattisgarh, Delhi, Gujarat, Haryana, Himachal Pradesh, Jammu and Kashmir, Jharkhand, Karnataka, Madhya Pradesh, Manipur, Odisha, Punjab, Rajasthan, Tamilnadu, Telangana, Uttar Pradesh, West Bengal, Daman and Diu
Salinity	2000 (Total Dissolved Solids) mg/L	16	Andhra Pradesh, Chhattisgarh, Delhi, Gujarat, Haryana, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Odisha, Punjab, Rajasthan, Tamilnadu, Telangana, Uttar Pradesh, West Bengal
Iron	0.3 mg/L	26	Andhra Pradesh, Assam, Arunachal Pradesh, Bihar, Chhattisgarh, Goa, Gujarat, Haryana, Jammu and Kashmir, Jharkhand, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Manipur, Meghalaya, Nagaland, Odisha, Punjab, Rajasthan, Tamilnadu, Telangana, Tripura, Uttar Pradesh, West Bengal, Andaman and Nicobar Islands
Nitrate	45 mg/L	21	Andhra Pradesh, Bihar, Chhattisgarh, Delhi, Gujarat, Haryana, Himachal Pradesh, Jammu and Kashmir, Jharkhand, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Odisha, Punjab, Rajasthan, Tamilnadu, Telangana, Uttar Pradesh, Uttarakhand, West Bengal

Source: Loksabha (2017a)

Elevated concentration of arsenic in groundwater is widely recognised as a global threat to human health and poses a challenge to drinking water supply in the affected areas. As per the BIS standards (IS 10500: 2012) maximum permissible limit of arsenic in drinking water was 50 μg/L, which vide an amendment in June 2015 has been changed to 10 μg/L (http://cgwb.gov.in/Documents/WQ-standards.pdf). According to the studies by CGWB and state government organisations, arsenic concentration in groundwater in excess of 10 μg/L has been reported from parts of

21 States in India (Loksabha 2017a). However, the contamination is mostly confined to the Indo-Ganga-Bramhaputra alluvial terrain covering parts of West Bengal, Uttar Pradesh, Bihar, Punjab, Haryana, Assam and Manipur (Saha 2009; Saha et al. 2009; CGWB 2014b; Sahu and Saha 2015). Significant instances of elevated arsenic have also been reported from the mineralised zones in hard rock areas of Chhattisgarh (Mukherjee et al. 2014) and Karnataka. In addition to above, isolated instances of arsenic contamination have also been reported from parts of another 12 States (Loksabha 2017a) as summarised in Table 2.1.

Salinity does not cause serious health effects as compared to arsenic or fluoride. Based on its origin, salinity could be broadly divided into inland salinity caused by rock-water interaction and coastal salinity caused by saline water intrusion. Inland salinity has been reported mainly from western, north-western and southern parts of India. The states largely affected by it are Rajasthan, Gujarat and Haryana. Inland salinity caused by high sulphate in ground water has also been reported from some parts of the country like central part of Chhattisgarh (CGWB 2006). Salinity originated from saline-water intrusion in coastal areas due to over pumping has been reported from the states of Tamil Nadu, West Bengal, Odisha, Gujarat and Andhra Pradesh (CGWB 2014b, c). Besides, percolation from spread sea-water during high tide or storm event also contributes to groundwater salinity in low lying coastal areas.

Excessive iron in groundwater has been reported from almost all states. Iron is so abundant in the natural environment that with favourable hydrochemical condition almost every geological formation can act as a source of iron in groundwater. Iron has been reported from parts of 26 States (Table 2.1).

Among anthropogenic contaminants, nitrate is the most widespread. It is the most ubiquitous chemical contaminant in the world's aquifers and the concentration levels are increasing (CGWB 2014b). Nitrogenous fertilizers and domestic wastes are the most important sources of nitrate in groundwater. Nitrate has been reported both from hard-rock as well as alluvial aquifers particularly from areas under intense cultivation (Saha and Alam 2014). Instances of elevated concentrations of nitrate have been reported from parts of 21 States (Table 2.1). Besides nitrate, zinc (Zn), mercury (Hg), manganese (Mn) have also been reported from some pockets (CGWB 2014b). Pesticides have also been reported from some pockets (Ghose et al. 2009).

7 Groundwater Issues and Challenges

7.1 Unequal Spatial and Temporal Distribution

There is a wide spatial variation in annual availabilities of groundwater resources within the country. Replenishable annual groundwater availability in India is 398×10^9 m^3, which translates into 120 mm for the country as whole, whereas it varies from more than 500 mm in the northern alluvial areas to less than 50 mm in the western part of the country (Fig. 2.2). More than 60% of the available resources are restricted to the northern alluvial terrains that occupy around 20% of the geographical area. In addition to unequal spatial distribution, intra- annual availabilities of the resources also vary within wide ranges. Reduced groundwater availabilities during the lean period (April–June) is apparent in many parts especially the Peninsular part covered by the hard rocks. Recent instance of drinking water scarcity in Latur district of Maharashtra is an example of reduced groundwater availability during lean period.

7.2 Dependence on Groundwater

While low availability in itself is a challenge in many parts of the country, high dependence on groundwater makes the situation worse. The United Nations (UN) led Drinking Water and Sanitation Decade (1981–1990) promoted construction of low cost bore wells especially in the hard rock areas around the world (Foster 2012). Though the drive was for drinking water, the introduction of fast drilling rigs resulted in the increase in construction of wells for irrigation as well. Introduction of energy efficient pumps and State subsidies on electricity used for pumping has also given a boost to groundwater extraction. In the last couple of decades groundwater accounted for 80% addition to net irrigated area in the country (Vijay Shankar et al. 2011). The increased dependence on groundwater has put the sustainability of groundwater resources at risk.

7.3 Over-Exploitation

Annual extraction of groundwater in India is the highest in the world, which even supersedes those of USA and China put together (NGWA 2016). Out of 6607 assessment units, there are nearly 2000 assessment units in which groundwater extraction has already exceeded 70% of the annual availability (Fig. 2.3). Around 16% (1071) of the assessment units have been categorised as ‘over-exploited’. Signs of unsustainable extractions are already apparent in terms of declining water levels, drying up of wells, reduced flow in the rivers etc.

7.4 Low Groundwater Development

Ironically, alongside over-exploitation, there are also areas where groundwater extraction is sub-optimal. Most of these areas are in the central, east central and north eastern parts of the country. Most of these areas are also irrigation deprived. The Government of India is contemplating a plan to promote groundwater based irrigation in these irrigation deprived areas where groundwater development is sub-optimal and utilizable resource is available.

7.5 Groundwater Contamination

Groundwater contamination has emerged as a major challenge in ensuring safe drinking water supply as nearly 85% of rural drinking water requirements and 50% of urban drinking water requirements are met from groundwater. Open dug wells used to be the main sources of rural drinking water supply in India in the 1970s. Pathogenic contamination of drinking water was widespread. In an attempt to overcome this, Governments promoted borewells as drinking water sources. This, in turn, gave rise to a new set of issues. Contaminants like arsenic, fluoride, nitrate, iron, salinity etc. have been reported from groundwater in many parts of the country.

8 Groundwater Management

8.1 Supply and Demand Side Interventions

Groundwater management refers to managing the resources in a sustainable manner. The core idea is that the utilisation should remain largely within the dynamic resources on a long-term basis. Off course, the dynamic or replenishable resource tends to increase as the resource is exploited more, which is reflected in higher fluctuation of pre and post monsoon water levels. Further, management objective is also to prevent or mitigate any long-term decline of water levels.

The management interventions can be grouped into two broad categories: supply management and demand management. The supply side intervention aims at enhancing the resource availability by rainwater harvesting, artificial recharge, recycling of wastewater or resorting to alternative sources. The demand management, on the other hand, envisages enhancing water use efficiency by adopting pressure irrigation, crop diversification, plugging unnecessary losses by seepage and evaporation between well head and irrigation field etc. The other important demand management tool is to address the groundwater-energy nexus. High rate of subsidy—even free electricity—is being provided to the farmers in most of the States and Union Territories. This issue is to be addressed with a rational approach like introducing appropriate pricing mechanism, incentivizing power/water conservation efforts, separating the electricity lines for use in pumps and regulating power supply for irrigation etc.

One essential link in groundwater management is mass awareness and public participation. Given the socio-economic condition in India, participatory groundwater management is advocated to be the most effective mode of popularizing efficient use of groundwater and implementing management interventions.

8.2 Groundwater Quality Management

Groundwater contamination is an impediment in ensuring safe drinking water as a majority of the populace in India is dependent on groundwater resources for meeting their drinking water needs. Tapping contamination-free aquifers, wherever available, is by far the most common way of dealing with groundwater quality. In the arsenic affected areas of West Bengal, Uttar Pradesh and Bihar, CGWB has constructed wells by sealing the upper arsenic contaminated aquifers and tapping the arsenic safe deeper aquifers (CGWB 2014b). Arsenic contamination reported from the hard-rock areas of Chhattisgarh has a strong geological control and CGWB has constructed water wells tapping water bearing zones, which are arsenic safe (Mukherjee et al. 2009). Post extraction (ex-situ) treatment of groundwater is another common mode of dealing with contaminated groundwater for drinking water supply, as in-situ treatment techniques are still in development stage (CGWB 2014b). Awareness regarding available safe sources, water-borne diseases etc. can greatly reduce the vulnerability to groundwater contamination.

With increasing instances of anthropogenic pollution, prevention of contamination has emerged as an important issue. Proper identification of waste dumping sites, reducing excessive use of fertilizers and pesticides, treatment of domestic and industrial wastes and protecting recharge areas are some of the ways through which man-made groundwater contamination can be prevented. While there are laws, public awareness and participation is vital to prevent groundwater contamination.

8.3 Groundwater Legislation

Regulating groundwater use is one of the ways to manage demand and it is a huge challenge for India as the rights of groundwater extraction is tied to the land ownership. As per the existing legal framework in India, groundwater does not seem to have a legal existence separate from the land (Koonan 2016). As per Sect. 7 of the India Easement Act, 1882 every owner of land has the right to collect and dispose within his own limits of all water under the land which does not pass in a defined channel. This legal proposition is still in force in India owing to Article 372 of the Constitution of India that keeps pre-Constitution laws in force until they are changed or repealed through subsequent laws.

However, alongside the existing law on ownership, the evolving statutory framework focuses on regulation of groundwater use. As per article 246 (read with seventh schedule List II), State Governments are entrusted with the power to adopt groundwater law under the Constitution. The necessity for regulation of groundwater withdrawal was felt in the 1970s, when signs of groundwater depletion started emerging due to extensive withdrawal. The Union Government circulated a Model

Bill in 1970 to all the States and Union Territories to enable them to enact suitable legislation for adopting control and regulatory measures in groundwater development. The model bill was subsequently revised in 1992 and 1996 (MoWR, RD, & GR 2016).

Though model bills were circulated since 1970, no noteworthy progress could be achieved until 1997. In response to a Public Interest Litigation (PIL) regarding alarming decline in groundwater levels due to overexploitation filed in 1985, the Hon'ble Supreme Court of India ordered Government of India to constitute an authority to regulate groundwater use and development under the Environmental (Protection) Act, 1986. As per the directions of the Hon'ble Supreme Court of India, Central Ground Water Authority (CGWA) was constituted in 1997. With creation of CGWA with clear statutory mandate and over-riding power for controlling and regulating the development and management of groundwater resources and equipped with the National Water Policy (MoWR 2002), the then Ministry of Water Resources (now it is Ministry of Water Resources, River Development and Ganga Rejuvenation) revised the model bill (MoWR 2005) and circulated it to the States for promulgation of State groundwater act and constitution of State Ground Water Authority, which would regulate and control the development and management of groundwater in the State. So far, 15 States/UTs have adopted and implemented the ground water legislation on the lines of Model bill 2005 (Loksabha 2017b). The States where separate groundwater law does not exist, regulation is implemented by the Central Ground Water Authority (CGWA). Subsequently, the model bill was again revised in 2011 (MoWR 2011) and 2016 (MoWR, RD, & GR 2016).

The groundwater laws in effect mainly envisage three regulatory tools (Koonan 2016): (i) Notification of areas in the state where groundwater situation requires regulatory interventions; (ii) Users in the notified areas are required to seek permission from the groundwater authority constituted under the groundwater law; (iii) Drilling agencies are required to register their machinery and are bound by the instructions issued by the groundwater authority. CGWA has notified 162 areas for regulation of groundwater development and management. Under the CGWA guidelines, in notified areas, no permission is accorded to extract groundwater through any energized means for any purpose other than drinking water. However, for non-notified areas, groundwater withdrawal by industries is regulated by means of guidelines/criteria as specified by CGWA (CGWA 2015).

Appropriate legislation is an important tool for prevention and control of groundwater pollution as well. Under the ambit of 'environment', the Environment (Protection) Act of 1986 of Government of India has provisions for protecting water resources from pollution. The Model Bill 2016 (MoWR, RD, & GR 2016), inter alia, envisages to 'reduce and prevent pollution and degradation of groundwater'. The model bill also stipulates that whoever contravenes the provisions of the Act by polluting or contaminating groundwater shall be strictly liable for any groundwater pollution they cause and shall be responsible for the cost of its remediation.

9 Conclusions

India, host to 16% of total population of world, has only 4% of total freshwater resources of the world. There is huge inequality in distribution of water resources within the country. Groundwater, which is the main source of fresh water in the country, is unevenly distributed. 60% of groundwater resources are restricted to the Indo-Ganga-Bramhaputra plains, which account for only 20% of the geographical area. Out of 6607 groundwater assessment units in the country 1071 have been categorized as ‘over exploited’, where annual extractions exceed annual recharge thereby threatening the sustainability of the sources. While over-exploitation is a major issue in the country, there are also areas where enough scope exists for further groundwater development. Adding to the woes is contamination of sources. Contaminants like arsenic, fluoride, nitrate, iron and salinity have been reported from groundwater in many parts of the country. Further, climate change is feared to contribute towards increased vagaries of monsoon affecting intra annual availabilities. Climate change induced sea level rise may increase saline ingress and increase in salinity of coastal aquifers. Groundwater is very much susceptible to deterioration in terms of quantity and quality due to unplanned and uniformed anthropogenic interventions and the results usually do not show until it is too late.

Artificial recharge, rainwater harvesting, treatment and recycling of wastewater are some of the supply side interventions that can help in augmenting resources. Reducing demand of groundwater through increasing water use efficiency, choosing less water intensive crops and regulating extractions are also effective management tools. Management interventions are a big challenge especially in view of the fact that more than 25 million abstraction structures are in operation in the country and most of them are private owned. Water is a ‘state subject’ in India and management interventions are implemented primarily by the respective State Governments. The Union Government plays a supportive role. The National Water Policy of India recognizes that water is a scarce natural resource and is fundamental to life, livelihood, food security and sustainable development. It proposes a framework for creation of a system of laws and institutions and for a plan of action with unified national perspective. The most important link in ensuring effective management is awareness and community participation.

References

BIS (2012). Indian standard-drinking water specification (second revision) IS 10500:2012, Bureau of Indian standards, Govt. of India (http://cgwb.gov.in/Documents/WQ-Standards.pdf)

BIS (2015). Amendment No. 1 to IS 10500:2012 drinking water specification (second revision), Bureau of Indian standards, Govt. of India (http://cgwb.gov.in/Documents/WQ-Standards.pdf)

CGWA (2015). Guidelines/Criteria for evaluation of proposals/requests for ground water abstraction (With effect from 16.11.2015). Central Ground Water Authority (CGWA). 27 p. http://www.cgwb.gov.in/CGWA/Documents/Revised%20guidelines_12112015.pdf accessed 15th May 2017.

CGWB (2006). State Report: Hydrogeology of Chhattisgarh. Unpublished Report, CGWB, NCCR, Raipur, India, 184 p.

CGWB (2010). Ground water quality in shallow aquifers of India. Central Ground Water Board, MoWR, RD&GR, Govt of India. http://www.cgwb.gov.in/WQ/gw_quality_in_shallow_aquifers.pdf. Accessed 15th May 2017.

CGWB (2012a). Aquifer systems of India. Central Ground Water Board, MoWR, RD&GR, Govt of India. http://www.cgwb.gov.in/AQM/India.pdf

CGWB (2012b). Water management challenges in islands of India. Central Ground Water Board, MoWR, RD&GR, Govt of India, 163 p.

CGWB (2014a). Dynamic ground water resources of India (As on 31st March 2011) Faridabad July 2014, http://www.cgwb.gov.in/Documents/Dynamic-GW-Resources-2011.pdf

CGWB (2014b). Concept Note On geogenic contamination of ground water in India with a special note on Nitrate. Central Ground Water Board, MoWR, RD&GR, Govt of India. http://www.cgwb.gov.in/WQ/Geogenic%20Final.pdf

CGWB (2014c). Status of ground water quality in coastal aquifers of India. Central Ground Water Board, MoWR, RD&GR, Govt of India http://www.cgwb.gov.in/WQ/Costal%20Report.pdf

CGWB (2016). Ground water year book of India 2014-15, CGWB, Ministry of WR, RD&GR, Govt of India. http://cgwb.gov.in/Ground Water/Ground%20Water%20Year%20Book%202014-15.pdf

Chatterjee, R. and Purohit, R. (2009). Estimation of Replenishable groundwater resources of India and their status of utilization. *Curr. Sci.*, **96(12)**, doi: https://doi.org/10.1007/s12665-009-0064-yCGWB2016.

Dar, F.A., Perrin, J., Ahmed, S. and Narayana, A.C. (2014). Review: Carbonate aquifers and future perspectives of karst hydrogeology in India. *Hydrogeol J*, **22(7):** 1493–1506.

Falkenmark, M. and Widstrand, C. (1992). Population and water resources: A delicate balance. Population Bulletin No. 3. Population Reference Bureau, Washington DC. http://www.ircwash.org/sites/default/files/276-92PO-10997.pdf.

Foster, S. (2012). Hard-rock aquifers in tropical regions: Using science to inform development and management policy. *Hydrogeol J*, **20(4):** 659-672, doi: https://doi.org/10.1007/s10040-011-0828-9.

FRRDF (1999). State-of-art report on the extent of fluoride in drinking water and the resulting endemicity in India. Fluorosis Research and Rural Development Foundation, New Delhi.

Ghose, N.C., Saha, D. and Gupta, A. (2009). Synthetic detergents (surfactants) and organochlorine pesticide signatures in surface water and groundwater of greater Kolkata, India. *Journal of Water Resources and Protection*. doi: https://doi.org/10.4236/jwarp.2009.14036.

Karanth, K.R. (2003). Ground Water Assessment Development and Management. Tata McGraw-Hill, New Delhi.

Ketabchi, H. and Ataie-Ashtiani, B. (2015). Review: Coastal groundwater optimization—advances, challenges, and practical solutions. *J Hydrol*, **23:** 1129–1154. DOI: https://doi.org/10.1007/s10040-015-1254-1

Koonan, S. (2016). Revamping the groundwater legal regime in India: Towards ensuring equity and sustainability. *Socio-Legal Review*, **12(2):** 45–73.

Kulkarni, H., Shah, M. and Vijay Shankar, P.S. (2015). Shaping the contours of groundwater governance in India. *Journal of Hydrology: Regional Studies*, **4(A):** 172–192. https://doi.org/10.1016/j.ejrh.2014.11.004

Loksabha2017a. Written reply to the question no. 3663 regarding contamination of ground water tabled in the Loksabha on 23.03.2017 http://164.100.47.194/Loksabha/Questions/QResult15.aspx?qref=51044&lsno=16

Loksabha2017b. Written reply to the question no. 4712 regarding rainwater harvesting tabled in the Loksabha on 30.03.2017. http://164.100.47.190/loksabhaquestions/annex/11/AU4712.pdf

MoWR (2002). National Water Policy – 2002. Ministry of Water Resources, Govt of India. http://wrmin.nic.in/writereaddata/NationalWaterPolicy/nwp20025617515534.pdf

MoWR (2005). Model bill 2005: Model Bill to regulate and control the development and management of ground water, 2005 http://cgwb.gov.in/NEW/CGWA/Documents/Model-bill.pdf

MoWR (2009). Report of the ground water resource estimation committee. Ministry of Water Resources, Govt. of India. 107 p. http://cgwb.gov.in/documents/gec97.pdf . Cited 18 November 2016

MoWR (2011). Model bill 2011: Model bill for the protection, conservation, management and regulation of groundwater. Draft of 18 October 2011 http://www.planningcommission.gov.in/aboutus/committee/wrkgrp12/wr/mb_wtrgrndsor_181011.pdf

MoWR (2015). A year of Inclusive Development in Water Resources sector. National Water Mission, Ministry of WR, RD&GR, Govt of India. http://www.nationalwatermission.gov.in/sites/default/files/COP%2021%20MoWR%20Booklet.pdf (accessed 17 January 2017).

MoWR, RD & GR (2016). Model bill for the conservation, protection, regulation and management of groundwater, 2016. Draft of 17 May 2016, Ministry of Water Resources, River Development and Ganga Rejuvenation, Govt of India. http://wrmin.nic.in/writereaddata/Model_Bill_Groundwater_May_2016.pdf

Mukherjee, A., Ray, R.K., Tewari, D., Ingle, V.K., Sahoo, B.K. and Khan, M.W.Y. (2014). Revisiting the stratigraphy of the Mesoproterozoic Chhattisgarh Supergroup, Bastar craton, India based on subsurface litho information. *J Earth Syst Sci*, **123(3):** 617–632.

Mukherjee, A., Tewari, D., Verma, J.R., Subramanian, S., Ray, R.K. and Devangan, R. (2009). Geogenic arsenic contamination to ground water in parts of Ambagarh Chowki Block, Rajnandgaon District, Chhattisgarh. *Bhujal News*, **24(2):** 40–58.

Najeeb, K. Md. and Vinaychandran, N. (2011). Groundwater Scenario in Lakshadweep Islands. *Journal Geological Society of India*, **78(4)**, doi: https://doi.org/10.1007/s12594-011-0095-3.

NGWA (2016). Facts about global groundwater usage compiled by NGWA, the groundwater association. http://www.ngwa.org/Fundamentals/use/Documents/global-groundwater-use-fact-sheet.pdf Cited 12 June 2016.

Rangarajan, R. and Athavale, R.N. (2000). Annual replenishable groundwater potential of India—An estimate based on injected tritium studies. *J Hydrol*, **234:** 38–53.

Ray, R.K., Mukherjee, A. and Mukherjee, R. (2014). Estimation of specific yields of individual litho-units in a terrain with multiple litho-units: A water balance approach. *J Geol Soc India*, **84 (2):** 221–225, doi: https://doi.org/10.1007/s12594-014-0126-y.

Ray, R.K., Syed, T.H., Saha, D., Sarkar, B.C. and Reddy, D.V. (2017). Recharge mechanism and processes controlling groundwater chemistry in a Precambrian sedimentary terrain: A case study from Central India. *Environ Earth Sci*, **76:** 136, doi: https://doi.org/10.1007/s12665-017-6435-x.

Saha, D. and Agrawal, A.K. (2006). Determination of specific yield using a water balance approach: Case study of Torla Odha watershed in Deccan Trap province, Maharashtra State, India. *Hydrogeol J*, **14:** 625–635, doi: https://doi.org/10.1007/s10040-005-0471-4.

Saha, D., Upadhyay, S., Dhar, Y.R. and Singh, R. (2007). The aquifer system and evaluation of its hydraulic parameters in parts of South Ganga Plain, Bihar, India. *J Geol Soc Ind*, **69:** 1031–1041.

Saha, D., Sinha, U.K. and Dwivedi, S.N. (2011). Characterization of recharge processes in shallow and deeper aquifers using isotopic signatures and geochemical behavior of groundwater in an arsenic-enriched part of the Ganga Plain. *Appl Geochem*, doi: https://doi.org/10.1016/j.apgeochem.2011.01.003.

Saha, D. and Alam, F. (2014). Groundwater vulnerability assessment using DRASTIC and Pesticide DRASTIC models in intense agriculture area of the Gangetic plains, India. *Environ Monit Assess*, doi: https://doi.org/10.1007/s10661-014-4041-x.

Saha, D., Dwivedi, S.N. and Singh, R.K. (2013). Aquifer system response to intensive pumping in urban areas of the Gangetic plains, India: The case study of Patna Urban area. *Environ Erth Sci*, doi: https://doi.org/10.1007/s12665-013-2577-7.

Saha, D. (2009). Arsenic groundwater contamination in parts of Middle Ganga Plain, Bihar.*Current Sci*, **97:** 753–755.

Saha, D., Sreehari, S.M.S., Dwivedi, S.N. and Bhartariya, K.G. (2009). Evaluation of hydrogeochemical processes in arsenic contaminated alluvial aquifers in parts of MidGanga Basin, Bihar, Eastern India. *Environ. Earth Sci.*, doi: https://doi.org/10.1007/s12665-009-0392-y.

Saha, D., Sahoo, S. and Chandra, P.C. (2010). Arsenic safe alternate aquifers and their hydraulic characteristics in contaminated areas of Middle Ganga Plain, Eastern India. *Environ Assess and Monit*, doi: https://doi.org/10.1007/s10661-010-1535-z.

Sahu, S. and Saha, D. (2015). Role of shallow alluvial stratigraphy and Holocene geomorphology on groundwater arsenic contamination in the Middle Ganga Plain, India. *Environ Erth Sci*, **73 (7):** 3523–3536, doi: https://doi.org/10.1007/s12665-014-3637-3.

Taylor, G.C. Jr. (1959). Ground Water provinces of India. *Economic Geology*, **54(4):** 683–697.

UNESCO (2008). Groundwater Resources of Asia. BGR, Hannover/UNESCO, Paris, https://www.whymap.org/whymap/EN/Downloads/Continental_maps/contimaps_node_en.html

UN-Water (2017). Wastewater the untapped resource. The United Nations World Water Development Report 2017. United Nations Educational, Scientific and Cultural Organization, Paris.

Vijay Shankar, P.S., Kulkarni, H. and Krishnan, S. (2011). India's Groundwater Challenge and the Way Forward. *Economic and Political Weekly*, **XLVI(2)**, January 8.

White, I. and Falkland, T. (2010). Management of freshwater lenses on small Pacific islands. *Hydrogeol J*, **18(1):** 227–246.