1 Hydrogeological Research in India in Managing Water Resources

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INTRODUCTION

India is a vast country with a total geographical area of about 3.28×10^6 km^2. Due to diversified geological, climatological and physiographic setup, groundwater situations in different parts of the country are divergent. Uneven distribution of surface water in space and time, man's interference, and over-exploitation of groundwater have caused regional imbalances in the supply and demand of water both in the alluvial tract of north India and in the hard rock formations of Peninsular India. The total annual water resources of India are about 1960 km^3. The utilizable water resource is 1140 km^3 (690 km^3 from surface water and 450 km^3 from groundwater). The present utilization is 750 km^3 (500 km^3 from surface water and 250 km^3 from groundwater). The projected demand for the year 2025 is 1050 km^3 indicating that by that point of time the total available water resources have to be put to use.

Groundwater has to fulfill about 33% of the water demand by the year 2025. Availability of groundwater varies from free flowing wells in parts of Indo-Gangetic plains to deep aquifers (>100 m) in Rajasthan depending on the hydrogeological conditions. Also, availability of groundwater in hard rock areas depends on the thickness of weathered material and fractures and fissures.

In view of the above, there is a need to understand the distribution and occurrence of groundwater in different hydrogeological situations. In this article, the hydrogeological setup of the country and occurrence of groundwater in different geological formations have been presented. Also, the research carried out in the areas of groundwater recharge, water quality and remote sensing and GIS have also been included.

WATER RESOURCES OF INDIA—AVAILABILITY AND DEMANDS

The present population of India is about 105 billion. It has mainly tropical climate but certain parts of the country in the west and in the peninsular region have semi-arid to arid climate.

India is bestowed with large resources of surface water and groundwater. However, their distribution both in space and time is highly variable due to the monsoon type of climate. The average annual rainfall is of the order of 1170 mm which brings about 4000 km^3 of water and about 200 km^3 flows in from the neighbouring countries. Evapotranspiration rates are high causing a total loss of about 1820 km^3 of water to the atmosphere. A water balance prepared by the National Commission of Agriculture is given in Fig. 1. The total water resources of all the river basins in the country are about 1869 km^3. Due to topographic limitations, only about 690 km^3 of water is considered as utilizable flow, out of which at present only about 500 km^3 is being used. The rest presently flows down unused either through surface flow or via groundwater to the oceans.

The maximum utilization of surface water is in Indus, Krishna, Kaveri, Sabarmati and Mahi river basins, while that in Ganga, Brahmaputa, Mahanadi and Narmada is low. Out of 1869 km^3 annual surface water potential, as much as 585.6 km^3 or 31.1% is in Brahmaputra Basin where due to non-availability of sufficient irrigable land only 24 km^3 is considered utilizable.

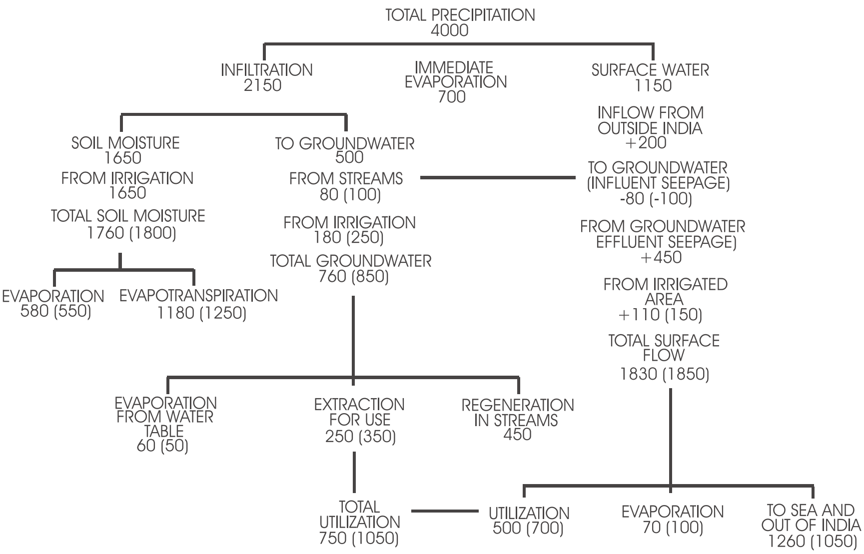

Figure 1. Approximate annual water resources of India in 2000 and 2025 AD (in km^3). The values in brackets are those anticipated for 2025 AD (Singh, 1997).

The river Brahmaputra carries more water per unit area of the basin than any other river in the world and is also one of the major sediment transporting rivers of the world, second only to the Yellow River of China.

The utilizable annual water resources of India are about 1140 km^3 out of which 690 km^3 is from surface water and 450 km^3 from groundwater sources. The utilization for the year 2000 and the projected annual demands of water for the year 2025 are given in Table 1.

Table 1: Estimates of Annual Water Demand and Water Distribution in India (in km^3)

Sl. No.	*Purpose*	*Year 2000*	*Year 2025*
Annual Water Demand			
1.	Domestic use	33	52
2.	Industrial	30	120
3.	Energy	27	71
4.	Irrigation	630	770
5.	Other uses	30	37
	Total	750	1050
Annual Water Distribution			
	Surface water	500	700
	Groundwater	250	350

(*Source:* Singh, 1997)

Table 1 indicates that out of total water utilized in the country, 84% is used for irrigation, about 4.4% for drinking and municipal use, 4% for industry, 3.6% for energy development and the remaining 4% for other purposes. Table 2 also shows that nearly the entire utilizable water resources of the country would be required to be put to use by the year 2025.This is mainly on account of increased demand of water for irrigation required to grow more food grain for the increasing population which is estimated to reach about 1.25 billion by the year 2025. Even at present there are indications of over-exploitation of groundwater as manifested by the lowering of water table in several areas. Therefore, there is an urgent need for chalking out suitable strategies for planning, development, conservation and management of available water resources in an optimal way.

GROUNDWATER RESOURCES

The assessment of water resources of the country dates back to 1949, Dr. A.N. Khosla (1949) estimated the total average annual run-off of all the river systems in India as 1674 km^3 (167.4 million hectare meter [Mham]), based on empirical formula which included both the surface and groundwaters. Since then various Working Groups/Committees/Task Force, constituted by Government of India, have made attempts to estimate the groundwater resources of the country. But, due to paucity of scientific data and incomplete understanding of the parameters involved in recharge and discharge processes, all these estimations were tentative and at best approximation.

The National Commission on Agriculture (1976) assessed the total groundwater resources of the country as a whole, taking into account the total precipitation, its distribution, evaporation from the soil, and sub-soil percolation. The groundwater recharge was worked out from the total quantity of water that percolated into the soil. The Commission assessed the groundwater resources as 670 km^3 (67 Mham), excluding soil moisture. The usable groundwater resource was assessed as 350 km^3 (35 Mham), of which 260 km^3 (26 Mham) was considered as available for irrigation. It further worked out the ultimate irrigation potential from groundwater as 400,000 km^2 (40 Mha) based on utilizable groundwater resource of 260 km^3 (26 Mham) and an average requirement of 0.65 hectare meter depth of groundwater to irrigate a cropped hectare, in contrast to 0.90 hectare meter of surface water, as conveyance losses are higher in the latter case.

This was the first exercise for conversion of the volume of groundwater to the area to be irrigated. The water requirement of crops was based on the average depth of gross irrigation application at the source per crop hectare.

The first attempt to estimate the groundwater resources on scientific basis was made in 1979. Agriculture Refinance and Development Corporation constituted a High Level Committee, Ground Water Over Exploitation Committee to recommend definite norms, for groundwater resources computations. Based on these norms the State Governments and the Central Ground Water Board computed the gross groundwater recharge as 467.90 km^3 (46.79 Mham) and the net recharge (70% of the gross) as 324.9 km^3 (32.49 Mham). This committee had, however, recommended that the methodology be revised with increasing availability of data.

Subsequently, Government of India constituted another committee to go into various aspects of the problems of the groundwater development. This committee examined in depth a large volume of hydrogeological and related data generated by the Central Ground Water Board through nation-wide surveys, exploration and 12 water balance projects, completed till then, and area oriented studies carried out by the State Ground Water Organizations. The Ground Water Estimation Committee came up with a revised methodology for assessment of groundwater potential and evolved new norms in 1984. Based on these norms the annual replenishable groundwater resources of the country were worked out to be 453.30 km^3 (45.33 Mham). Keeping a provision of 15% (69.8 km^3) for drinking, industrial and other uses the utilizable groundwater resource for irrigation was computed 383.40 km^3 (38.34 Mham) per year. The ultimate irrigation potential in terms of area based on the state-wise assessment was estimated as 80.38 Mha. In this assessment, the irrigation requirement varies from 0.36 m/ha in Uttar Pradesh to 1.20 m/ha in Assam. Even in individual states, a range of values of irrigation requirement was considered viz. 0.36 to 0.937 m for Tamilnadu, 0.4 to 0.75 m for Maharashtra, etc.

Ministry of Water Resources, Government of India, revised the groundwater resources in 1995. According to the report, the total rechargeable groundwater resources in the country are computed as 43.19 m.ha.m. The available groundwater resource for irrigation is 36.08 m.ha.m, of which the utilizable quantity is 32.47 m.ha.m. The utilizable irrigation potential of the country has been estimated as 64.05 m.ha., based on crop water requirement and availability of cultivable land. The stage of groundwater development is estimated as 55.23% based on irrigation potential created in the country (35.38 m.ha.). Basin wise groundwater potential is given in Table 2.

Table 2: Basin-wise Ground Water Potential of India

Sl. No.	*Name of Basin*	*Total Replenishable Ground Water Resources (km^3)*
1.	Brahmai with Baitarni	4.05
2.	Brahmaputra	26.55
3.	Cambai Composite	7.19
4.	Cauvery	12.30
5.	Ganga	170.99
6.	Godavari	40.65
7.	Indus	26.49
8.	Krishna	26.41
9.	Kutch and Saurashtra Composite	11.23
10.	Madras and South Tamil Nadu	18.22
11.	Mahanadi	16.46
12.	Meghna	8.52
13.	Narmada	10.83
14.	Northeast Composite	18.84
15.	Pennar	4.93
16.	Subarnarekha	1.82
17.	Tapi	8.27
18.	Western Ghat	17.69
	Total	431.42

In order to establish changes in groundwater levels, Central Ground Water Board has established a network of about 15,000 stations covering various parts on the country. In addition to these, State Ground Water departments are also monitoring the water levels in their respective States. The observations for the year 1980-2000 indicate a decline of about 4 m during this period covering almost all the States. In the capital city of Delhi, a decline of more than 5 m has been reported. The overall decline in water table is due to greater demand of water for irrigation, domestic and industrial uses as well as decreasing groundwater recharge as a result of urbanization. As the pace of development is not uniform, there are areas, which are greatly affected while in other parts the problem is not so severe.

In view of the recurring problems of drought, Government of India has launched an Accelerated Programme of Groundwater Exploration and development. Under this programme, tube wells are being drilled as "sanctuary wells", which will be used only during the drought period, as a crisis management measure exclusively for drinking water needs.

HYDROGEOLOGICAL SETUP

India is a vast country having diversified geological, climatological and physiographic setup, giving rise to divergent groundwater situations in different parts of the country. The rocks, which control the movement of groundwater, vary in age from Archean to Recent and also vary widely in composition and structure. The landforms vary from rugged mountains of the Himalayas to flat alluvial plains of rivers and coastal tracts, and the aeolian deserts of Rajasthan. The rainfall also varies from <100 mm in parts of Rajasthan to >10,000 mm in Meghalaya. The topography and rainfall virtually control the surface runoff and consequently the groundwater recharge. Fig. 2 shows the major aquifers in India.

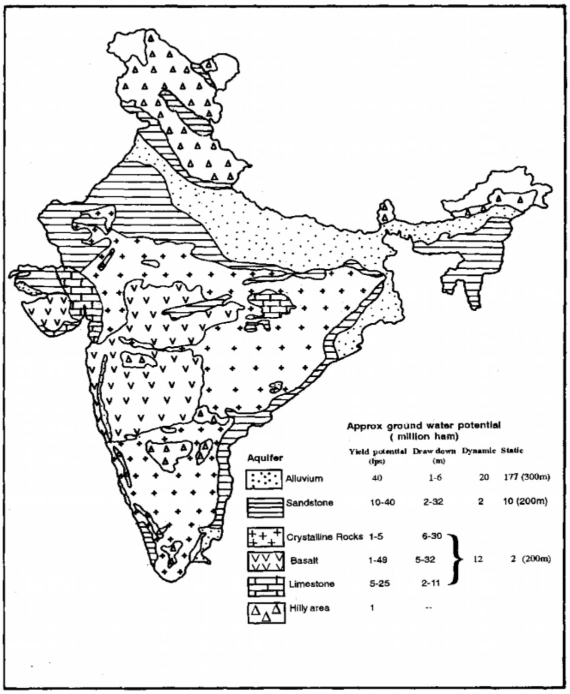

Figure 2. Distribution of major aquifers in India (*Source:* Raju, 2003).

The large alluvial tract in the Sindhu-Ganga-Brahmaputra plains, extending over a distance of 2000 kms from Punjab in the west to Assam in the East, constitute one of the largest and most potential groundwater reservoirs in the world. These aquifer systems are extensive, thick, hydraulically interconnected and moderate to high yielding. To the north of this tract all along the Himalayan foot hills, lies the linear belt of Bhabar piedmont deposits, and the Tarai belt down slope with characteristic auto flowing conditions.

Hydrogeologically alluvial formation consists of unconsolidated sand, silt and clay with occasional beds of gravel extending to a depth of more than one km at some places. In a narrow belt in the north, at the foot of the Himalayas, artesian aquifers, under free flowing conditions exist at a depth of 50 to 100 m. Possibilities of deep confined aquifers as a potential source of water is indicated from deep drilling carried out for oil exploration at some places (Jones, 1987). The area is also bestowed with good rainfall and recharge conditions. Ground water is mainly used for irrigation in addition to domestic and other uses. Tube well irrigation is being practiced in this area from the last more than one hundred years.

The next older formation of Cenozoic age consisting of unconsolidated to semi-consolidated sandstone and shale occupy parts of coastal areas and also in the northeast. Under favourable conditions these formations form artesian aquifers as in parts of Cambay basin in the west and Neyveli in Tamilnadu in South India.

The main volcanic suite of rocks is represented by Deccan Traps occupying an area of more than 500,000 km^2 in the western and central parts of the country. A number of basaltic flow units are identified of age varying from Upper Cretaceous to Lower Eocene. Main source of groundwater is from the weathered, fractured and vesicular horizons. At places different layers of basalt form a multi-aquifer system. Parts of this area has semi-arid climate due to which recharge is limited and availability of groundwater is poor.

The Gondwanas are represented by semi-consolidated sandstone, shale and coal beds, which were deposited in the structurally controlled faulted basins. They are fresh water deposits of age varying from Permo-Carboniferous to Late Jurassic. They also form multi-aquifer system. Uncontrolled mining has resulted in the flooding of mines causing great loss of life of miners.

Most part of Peninsular India is occupied by a variety of hard and fissured formations, including Crystalline, trappean basalt and consolidated sedimentaries (including carbonate rocks), with patches of semi-consolidated sediments in narrow intracratonic basins. Rugged topography and compact and fissured nature of the rock formations combine to give rise to discontinuous aquifers, with limited to moderate yield potentials. The near surface weathered mantle forms the all important groundwater reservoir, and the source for circulation of groundwater through the underlying fracture systems. In the hard rock terrain, deep weathered pediments, low-lying valleys and abandoned river channels generally contain adequate thickness of porous material, to sustain groundwater development under favourable hydrometeorological conditions. Generally, the potential water saturated fracture systems occur down to 100 m depth, and in cases yield even up to 30 litres per second (Ips). The friable semi consolidated sandstones also form moderate yielding aquifers, and auto flowing zones in these formations are not uncommon. Shallow large diameter dug-wells and small diameter bore-well s are the main source of water supply for domestic and irrigation purposes. The yield characteristic of wells varies widely. Over exploitation of groundwater has caused considerable lowering of water table. Recent studies have indicated the presence of potential aquifers at deeper levels due to the presence of deep-seated fractures along lineaments. These lineament zones are found to be highly productive for construction of bore-well s (Singhal and Gupta, 1999).

Consolidated sedimentary formations viz., sandstone, shale and limestone of Pre-Cambrian age occur as isolated basins in different parts of the country. The permeability of the rocks is usually poor. Limestone is usually massive and lack in the development of secondary porosity due to the lack of solution activity except in some parts of western and Peninsular India.

The coastal and deltaic tracts in the country form a narrow linear strip around the peninsula. The eastern coastal and deltaic tract and the estuarine areas of Gujarat are receptacles of thick alluvial sediments. Though highly productive aquifers occur in these tracts, salinity hazards impose quality constraints for groundwater development. In this terrain, groundwater withdrawal requires to be regulated so as not to exceed annual recharge and not to disturb hydro-chemical balance leading to seawater ingress.

The high relief areas of the northern and northeastern regions occupied by the Himalayan ranges, the hilly tracts of Rajasthan and peninsular regions with steep topographic slope, and characteristic geological set-up offer high run-off and little scope for rainwater infiltration. The groundwater potential in these terrains are limited to intermontane valleys. Distribution of hydrogeological units in India is given in Table 3.

Table 3: Distribution of Hydrogeological Units in the country and their potential

Geologic Age	*Stratigraphic Unit*	*Rock Formation*	*States/Hydrogeological Characters*
Consolidated Formations			
Jurassic Upper Cretaceous to Eocene	Rajmahal Traps, Deccan Traps.	Basalts, Dolerites, Diorites and other acidic derivatives of Basaltic magma.	Occur in West Bengal, Bihar, Madhya Pradesh, Gujarat, Maharashtra, Andhra Pradesh and Karnataka. Hydrogeological characteristics almost similar. Fractured and Vesicular basaltic layers and inter-trappean sedimentaries are productive. Yield up to 5 lps. Storativity: 1 to 4%. Hydraulic conductivity 5 to 15 m/day. Unconfined shallow aquifers and leaky-confined/confined deeper aquifers.
Pre-Cambrian	Cuddapahas Delhi and Equivalent Systems.	(a) Consolidated Sandstones, Shales, Conglomerates. (b) Limestones, Dolomites (c) Quartzites, Marbles (d) Intrusive Granites and Malani Volcanics.	Occur in all States. These formations are devoid of primary porosity. Weathering and denudation, structural weak planes and fractures impart porosity and permeability in the rock mass. Solution cavities (caverns) in carbonate rocks at places, give rise to large ground water storage/circulation.
Archaean	Archaean Complex Dharwars, Aravalis and Equivalent formations.	(a) Granites, Gneisses, Charnokites and Khondalites (b) Schists, Slates, Phyllites Granulites. (c) Banded Haematite Quartzites (Iron ore series)	The ground water circulation is generally limited within 100 m depth. Storativity value of unconfined aquifer is generally low (0.2% to 3%). Hydraulic conductivity varies widely depending on fracture incidence (2 to 10 m/day). Leaky confined/confined aquifers may be present in layered formations. Granites and granite-gneisses are the most productive aquifers. Yield range 2 to 10 lps and more.

(Contd.)

(*Contd.*)

Geologic Age	*Stratigraphic Unit*	*Rock Formation*	*States/Hydrogeological Characters*
Semi-consolidated Formations			
Tertiary		(a) Nummulitic Shales and Limestones (b) Carbonaceous Shales (c) Sandstones (d) Shales (e) Conglomerates (f) Ferrugineous (g) Sandstones (h) Calcareous Sandstones (i) Pebble Beds (j) Boulder-Conglomerate (k) Sands (l) Clays	The hydrogeological potential of these formations is relevant only in the valley areas. Lower Siwaliks and their equivalents in Himachal Pradesh, Jammu and Kashmir, Assam, Punjab, Haryana, Uttar Pradesh and Sikkim generally do not form potential aquifers. The Upper Siwaliks have moderate groundwater potential in suitable topographic locations. Tertiary sand stones of Rajasthan, Gujarat, Kutch, Kerala, Orissa, Tamil Nadu, Andhra Pradesh, West Bengal and North Eastern States have moderate to moderately good yield potentials up to 28 lps. Possess moderate primary porosity and hydraulic conductivity.
Upper Carboniferous to Jurassic	Gondwanas	(a) Boulder-Pebble Beds (b) Sandstones (c) Shales	Occur in Bihar,. Maharashtra, Andhra Pradesh, Orissa, Madhya Pradesh, Gujarat, Rajasthan and Tamil Nadu.
	Jurrasic of Kutch and Rajasthan Baghbeds Lametas and Equivalents.	(a) Coal Seams (b) Sandstones (c) Calcareous Sandstone (d) Shales (e) Quartzites (f) Limestones	These formations do not have wide regional distribution, Possess moderate primary porosity and hydraulic conductivity. Karstified limestones are good water yielders. Friable sandstones in Barakars and Kamthis (Lower Gondwana) and their equivalent formations possess moderately good potential. Yield up to 14 lps.

(*Contd.*)

(*Contd.*)

Pleistocene to Recent	(a) Fluvio Glacial deposits	(a) Mixed Boulders, Cobbles, Sands and Silts	The morainic deposits occupy valleys and gorges in interior Himalayas. Karewas (Kashmir Valley) are lacustrine deposits displaying cyclic layers of clayey, silty and coarser deposits with intervening boulder beds. Locally significant hydrogeological potential.
	(b) Glacio-Lacustrine deposits	(b) Conglomerates, Sands Gravels, Carbanaceous shales and Blue Clays.	
	(c) Piedmont and Himalayan Foot Hill deposits	(c) Boulders, Cobbles, Pebble Beds, Gravels, Sands, Silt and Clays.	The Bhabhar piedmont bell contains many productive boulder–cobble gravel-sand aquifers. The water table is deep. Forms recharge zone for deeper aquifers of alluvial plains in south. Tarai belt is down-slope continuation of Bhabhar aquifers. The deeper confined aquifers display flowing artesian conditions. Shallow water table yields up to 28 lps.
	(d) Alluvial Plains (Older and Newer Alluvium)	(d) Clays and Silts, Gravels and Sands of different mix. Lenses of Peat and Organic matter, Carbonate and Siliceous Concretions (Kankar).	Occur widespread in the Indo-Ganga-Brahmaputra alluvial plains. Form the most potential groundwater reservoirs with a thick sequence of sandy aquifers down to great depths. The unconfined sand aquifers sometimes extend down to moderate depth (125 m). Deeper aquifers are leaky-confined/confined. The older alluvium is relatively compact. The unconfined aquifers generally show high storativity (5 to 25%) and high transmissivity (500 to 3000 m^2/day).

(*Contd.*)

(*Contd.*)

Geologic Age	*Stratigraphic Unit*	*Rock Formation*	*States/Hydrogeological Characters*
Unconsolidated Formations			
			The deeper confined aquifers generally occurring below 200 to 300 m depth have low storativity (0.005 to 0.0005) and transmissivity (300 to 1000 m^2/day). Highly productive aquifers yield up to 67 lps and above. The potentials of peninsular rivers alluvium are rather moderate with yield up to 14 lps. But the alluvial valley fill deposits of Narmada, Tapi, Purna basins, 100 m thick, sustain yield upto 28 lps. The quality of ground water at deeper level is inferior. (Storativity 4×10^{-6} to $1.6 \times 1.0^{-2)}$ and transmissivity 100 to 1000 m^2/day). Thick alluvial sequences in deltas of major rivers on the eastern coast and in Gujarat estuarine tracts. Hydrogeological potential is limited by salinity hazards.
	(e) Aeolian deposits (sandstones)	(e) Very fine to fine sand and silt.	The aeolian deposits occurring in West Rajasthan, Gujarat, Haryana, Delhi and Punjab have moderate to high yield potentials; are well sorted and permeable; lie in arid region; natural recharge is poor and water table is deep.

(*Source:* CGWB, 1995)

GROUNDWATER RECHARGE STUDIES

Groundwater recharge has been measured at many locations in India by the tritium tagging or tritium injection method. The method is based on the assumption that the soil water in the unsaturated zone moves vertically downward as discrete layers. Water added on the surface either as precipitation or irrigation will move downwards by pushing the older water beneath and this in turn will push the still older water further below, thereby the water from the unsaturated zone is added to the groundwater reservoir. This flow mechanism is known as the piston flow. Therefore, the vertical movement of the injected tritium can be monitored in the soil column. The position of the tracer is indicated by a peak or a maximum in the tritium activity versus depth plot. However, molecular diffusion, dispersion and aquifer heterogeneties may cause broadening of the peak. The methodology provides spot measurements of natural recharge.

This method has been used by a number of workers in different hydrogeological environments in India. Measurements have been carried out for the last more than 25 years in 35 watersheds, water basins and administrative blocks by various research workers (Table 3).

Natural recharge rates obtained from the tritium injection method were compared with other methods e.g. water level fluctuation and groundwater modelling. The recharge rates calculated from tritium injection method range from 24 to 198 mm/yr. or 4.1 to 19.7% of the local average seasonal rainfall depending upon the hydrogeological and climatic conditions (Table 4). The replenishable groundwater potential of India, for normal monsoon years based on tritium injection method, is calculated as 476×10^9 m^3 per year.

Table 4: Rainfall recharge measurements in India using tritium injection method

SI.. No.	*Basin/watershed/ Blocks*	*Main rock types*	*Rainfall (mm yr⁻¹)*	*Natural recharge derived*		
				Median (mm yr⁻¹)	*Mean (mm yr⁻¹)*	*Rainfall (%)*
1.	Punjab	Alluvium	460	35	56	12.2
2.	Haryana	Alluvium	470	43	70	14.9
3.	Western Uttar Pradesh	Alluvium		174	195	19.7
4.	Churu district, Rajasthan	Alluvium	491	67	62	12.6
5.	Godavari-Puma basin, Maharashtra	Basalt	652	50	56	8.6
6.	Lower Maner basin, Warangal and Karimnagar dists. Andhra Pradesh	Sandstone and shale	1250	103	117	9.4
7.	Neyveli basin, Tamilnadu	Sandstone	1398	150	181	12.9
8.	Neyveli basin, Tamilnadu	Alluvium	1004	50	161	16.0
9.	Noyil basin, Tamilnadu	Granite, Gneiss	715	35	69	9.6

(after Rangarajan and Athavale, 2000)

Studies in the hard rock terrains covered with black cotton soil in basaltic terrain and red lateritic soil in granitic areas indicate that a minimal rainfall of about 246 mm and 412 mm are required for initiation of deep percolation in red and black cotton soils respectively. However all of this will not be available for utilization as part of it will be lost to base flow and effluent seepage to surface drainage system. This also does not include other sources of recharge such as return flow from irrigation.

WATER QUALITY

In addition to the problem of inland salinity, overexploitation of groundwater has resulted in seawater intrusion in coastal areas. This problem is more severe in the coastal parts of Gujarat, Orissa, Tamilnadu and Kerala. Further, higher concentration of fluoride, iron and arsenic is reported from some areas. Higher concentration of fluoride (more than the permissible limit of 1.5 mg/lit) is reported from parts of Andhra Pradesh, Tamilnadu, Rajasthan and Uttar Pradesh. The cause of high fluoride in these areas is geogenic i.e. due to the dissolution of fluoride bearing minerals. At some places, deflouridation plants are installed to remove high concentration of fluoride.

The occurrence of arsenic in groundwater, reported in recent years from parts of West Bengal, has caused great concern. In West Bengal, life of more than five million people is at risk due to high As in groundwater and already about half a million people suffer from various arsenic related diseases. Similar problem is reported from the neighbouring country of Bangladesh where high concentration of arsenic (0.3 to 1.1 mg/lit) is reported from shallow alluvial and deltaic aquifers in the depth range of 15 to 75 m below the ground surface. The permissible limit of arsenic in drinking water in India is 0.05 mg/lit, while the WHO has put a limit of 0.01 mg/lit.

Studies in West Bengal by the scientists of the Bhaba Atomic Research Center (BARC) and CGWB show that groundwater from shallow unconfined aquifers (depth 20 to 80 m) has low dissolved oxygen, negligible SO_4 and higher concentration of As (0.5 to 1.0 mg/lit or more), and bicarbonate; pH being above 7. In most of the areas the arsenic concentration is localized. Higher concentration of As is in areas where clay pockets predominate. Isotope data indicate modern recharge to the shallow aquifer. Groundwater in deeper semi-confined to confined aquifers (>100 m) contains negligible amount of As and is much older in age (5000 to 13,000 years) indicating that these are palaeowaters. Surface water in these areas does not have any arsenic.

The cause of high arsenic in groundwater of both India and Bangladesh is somewhat controversial. Some workers attribute it to the presence of arsenic bearing pyrite in the clay, silt and peat formations interbedded with alluvial aquifers. Lowering of water table, due to excessive withdrawal of groundwater, has resulted in the oxidation and leaching of As from the sediments.

According to other scientists, arsenic, which is adsorbed on the iron hydroxide surface, is released to groundwater under reducing conditions (Mukherje et al., 2001). They have also argued that detrital pyrite or arsenopyrite is absent from the aquifer in these areas.

Studies by the CGWB in West Bengal have indicated the presence of arsenic-free aquifers in the depth range of 200 to 250 m below ground level which can be tapped by constructing deep tube wells. Mitigation is difficult given the scale of the problem as well as social and economic factors. Options include use of deep groundwater (>150 m), use of disinfected groundwater from dug-wells, rainwater harvesting, and treatment of contaminated groundwater and surface water.

Groundwater having more than the maximum permissible limit of 1.0 mg/lit of iron is reported from high rainfall areas in eastern states and northeastern states. It is attributed to the dissolution of iron oxides in laterites and other iron bearing minerals. Iron-removal plants are installed at some places to provide safe drinking water in these areas.

The problem of acid mine drainage especially from high sulphur Tertiary coals of Assam in northeastern India is quite acute. In this area the problem is aggravated due to high rainfall of the order of 400 cm/yr. The mine drainage water is highly acidic (pH = 2.3 to 4.0) and contains more than 3000 mg/lit of sulphate and about 300 mg/lit iron.

Dumping of industrial waste and sewage into surface water-courses cause widespread pollution resulting in large number of deaths due to water-borne diseases.

GROUNDWATER AUGMENTATION THROUGH ARTIFICIAL RECHARGE

The artificial recharge is being practiced for augmentation of groundwater reservoir and to provide sustainability to groundwater development in India. The schemes for artificial recharge are being implemented in different hydrogeological situations by CGWB and many State Groundwater Departments. A few case studies from different hydrogeological setups are given herein under:

Basaltic Terrain—Maharashtra

Over-exploitation of groundwater for orange cultivation has depleted the groundwater resources in parts of Amravati district, Maharashtra. Hydrogeological studies have brought out that the watershed WR-2 covering 488 km^2 area has surplus monsoon runoff of about 98.9 million cubic metres (MCM) which can be conserved through simple artificial recharge structures like percolation tanks and check dams (cement plugs). The efficiency of these structures constructed at suitable locations with appropriate design in case of percolation tanks is 91% and for cement plugs 94%. The benefited area in case of percolation tanks with gross storage capacity varying from 71 to 220 thousand cubic metres (TCM) varied from 60 to 120 hectares (ha) during 1997-98 and benefits extended up to 1.5 km down stream of percolation tanks. In case of cement plugs with storage capacity varying from 2.10 TCM to 7.42 TCM varied from 3 to 15 ha during 1997-98.

Alluvial Aquifers Bordering Mountain Front—Maharashtra

The prominent regional aquifer system for Tapi Alluvial basin paralleling Saturn Mountain front is being extensively developed to meet the water requirement of cash crops like banana and sugarcane. This has led to decline of water levels by more than 8-10 metres during last 10-15 years. Large number of wells have either gone dry or their yields have declined. The Central Ground Water Board carried out artificial recharge studies in TE-17 watershed in Jalgaon district. The sub-surface storage potential of watershed five metres below ground level was assessed as 85 million cubic metres (MCM) compared to surplus monsoon runoff of 29.7 MCM. Artificial recharge techniques like recharge through percolation tanks, recharge through existing dug-wells, recharge shafts and through injection tubewells were experimented. Percolation tanks in Bazada formation of Saturn foothills were found to be highly efficient with efficiency as high as 97% and capacity utilization going up to 400%. The zone of benefit extended to 5 km with benefited area up to 400 ha.

Percolation Tanks in Hard Rocks in South India

Artificial recharge by percolation tanks is an ancient practice of water conservation especially in the hard rock terrains of India. Hundreds of such tanks are constructed every year in drought prone areas to augment groundwater recharge from permeable river beds by constructing check dams/ dykes. Rate of infiltration from these tanks depend on local hydrogeological conditions, topography and storage characteristics of the tank. Studies in granites and basaltic terrains of South India indicate that the rate of recharge from percolation tanks vary from 9 to 12 mm/day. The rate of infiltration decreases with time due to silting. In ephemeral and seasonal streambeds, recharge rates are comparatively high due to the reworking/removal of silt during the dry period. Evaporation losses from the tanks are also high, being about 4 to 6 mm/day (Muralidharan and Rangarajan, 2001).

Coastal Area—Saurashtra, Gujarat

After detailed hydrogeological surveys and groundwater draft estimation, artificial recharge through pressure injection and surface spreading methods was experimented in the alluvial area around Kamliwara in the Central Mehsana. Source water for the test was drawn from the phreatic aquifer below the Saraswati riverbed. Since groundwater was used for artificial recharge, the injection water was devoid of silts and other impurities and chemically compatible with the water in aquifer getting recharged. The pressure injection experiment was conducted continuously for about 250 days with an average injection quantity of 225 cubic metres per day. During the recharge cycle, a rise in water level of five metres in the injection well (apparent built up of 11 m) and 0.6 to 1.0 m in wells 150 metres away from the injection well were observed.

In Mehsana area, artificial recharge experiments through spreading method were also conducted using canal water. A spreading channel of 3.3 metres width, 400 m length with 1 in 1 side slope was constructed and in which the canal water was fed for 46 days. The recorded build up in water level of 1.4 to 2 m was observed up to 15 m from the recharge channel and about 20 cm at distance of 200 m. The recharge rate of 260 cubic metres per day was estimated using an infiltration rate of 17 cm/day. Dissipation in recharge mound (1.42 m) was observed in 15 days.

Studies on control of salinity in the coastal Saurashtra using spreading and injection method have indicated that the recharge pit and the injection shaft can effect recharge at the rate of 192 and 2600 cubic metres per day respectively. Canal water was used for recharge studies.

Alluvial Areas of Ghaggar River Basin—Haryana

Central Ground Water Board, with the assistance of UNDP, carried out artificial recharge studies involving recharge through injection well in Kurukshetra District along Ghaggar river in Haryana. After construction and development of injection well, recharge experiment was conducted with a recharge rate of 40 LPS for 389 hours and with 22 LPS for another 24 hours. The experiment demonstrated that the hydrogeological conditions of the area are favourable for artificial recharge through injection method. The canal water quality was found to be suitable for injection.

REMOTE SENSING AND GIS APPLICATIONS

Since late 60’s many attempts have been made to explain spatial variability of groundwater occurrence in different terrain conditions using aerial photography and remote sensing. Ghosh and Singh (1975) have identified the control of palaeochannels on the occurrence and movement of groundwater in Rajasthan. Under National Drinking Water Mission, ISRO has identified and mapped favourable zones for groundwater exploration (ISRO, 1988).

Groundwater cannot be seen directly from the remote sensing data; hence its presence is inferred from identification of surface features, which act as an indicator of groundwater (Das et al., 1997; Ravindran and Jeyram, 1997).

Many researchers have used remote sensing and GIS techniques successfully for demarcating the groundwater potential zones in diverse geological setup (Raj and Sinha, 1989; Champati et al., 1993; Krishnamurththy et al., 1996; Saraf and Chaudhary, 1998; Shahid et al., 2000).

Department of Space have recently completed a project under drinking water mission in five states of the country (NRSA, 2000). Under this project different thematic maps—viz., geology, geological structures, geomorphology and recharge conditions have been prepared and the said maps have been integrated in GIS for demarcation of potential groundwater zones.

Jaiswal (2003) has developed an approach for identifying groundwater prospect zones in hard rock areas. The approach is based on information extracted on lithology, geological structures, landforms, landuse map prepared from remotely sensed data and drainage network, soil characteristics slope of terrain from conventional methods and studying all these data in GIS environment.

CONCLUDING REMARKS

India is a vast country with diverse hydrogeological conditions. Distribution and availability of groundwater depends on the type of aquifers. A lot of work has been done on exploration of groundwater and understanding the hydrogeological setup of the country. Modern techniques like isotopic tracers are being used to study the groundwater recharge and groundwater movement in different conditions. Remote sensing and GIS is also being used to identify the groundwater prospect zones.

REFERENCES

CGWB, 1995. *Ground Water Resources of India*. Faridabad, 147 pp.

CGWB, 2000. *Guide on Artificial Recharge to Ground Water*. Faridabad, 93 pp.

Champati Ray, P.K., Dave, V. and Roy, A.K., 1993. Groundwater Investigation Using Remote Sensing and GIS Technique- A case study in Manbazar-II Purulia-9 (WB). Proceeding of National Symposium (ISRS)-Remote Sensing Applications for Resources Management, Guwahati, India. 25-27, November, 1993.

Das, S., Behera, S.C., Kar, A., Narendra, P. and Guha, S., 1997. Hydrogeomorphological Mapping in Groundwater Exploration Using Remotely Sensed Data-A case study in Keunjhar district, Orissa. *Journal of the Indian Society of Remote Sensing*, **25:** 247-260.

Ghose, B. and Singh, S. 1975. Geomorphology of Prior and Present Drainage Networks and Their Control on Groundwater in Sandstone Formations, Jodhpur district, *Annual Report*, CAZRI, Jodhpur.

Jaiswal, R.K., Mukherjee, S., Krishnamurthy, J. and Saxena, R., 2003. Role of remote sensing and GIS technique for generation of groundwater prospect Zones Towards Rural Development—An approach. *International Journal of Remote Sensing*, **24:** 993-1008.

Jones, P.H., 1987. Deep Aquifer Exploration Project in the Ganges and Bengal Basins in India (Unpublished report), 54 pp.

Khan, M.A. and Moharana, P.A., 2002. Use of Remote Sensing and Geographic Information System in the Delineation and Characterization of Groundwater Prospect Zones. *Journal of the Indian Society of Remote Sensing*, **30:** 131-141.

Krishnamurthy, J., Venkatesa Kumar, N., Jayaraman, V. and Manivel, M., 1996. An Integrated Approach to Demarcate Groundwater Potential Zones through Remote Sensing and Geographic Information System. *International Journal of Remote Sensing*, **17:** 1867-1884.

Mukherje, P.K. et al., 2001. Arsenic-rich Phases in Aquifer Sediments from Southern West Bengal. *Journal of Geological Society of India*, **58:** 173-176.

Muralidharan, D. and Rangarajan, R. 2001. Replenishent of unconfined Hard Rock Aquifer and Improvement of Percolation Tank Efficiency. *In:* Singhal, D.C. et al. (Eds.) Proceedings International Symposium on Emerging Trends in Hydrology, **II:** 113-124.

National Institute of Hydrology, 1992. Hydrological Developments in India since Independence: A Contribution to Hydrological Sciences, Roorkee

NRSA, 2000. Rajiv Gandhi National Drinking Water Mission: Technical guidelines for preparation of groundwater prospects maps. NRSA/AD/GG/GD/TR:1/2000. NRSA, Department of Space, Hyderabad, India.

Raj, S. and Sinha, A.K., 1989. An Integrated Approach for the Delineation of Potential Groundwater Zones using Satellite Data: Case study, Udaipur District, Rajasthan. Asia-Pacific *Remote Sensing Journal*, **2:** 61-64.

Raju, K.C.B., 2003. Water conservation in Hard Rock Areas: A necessity. *In:* Singhal, B.B.S. and Verma, O.P. (Eds.), 2003. *S & T Inputs for Water Resources Management*. DST's Spl. Vol. 3, Indian Geological Congress, Roorkee. 173-195.

Ravindran, K.V. and Jeyaram, A., 1997. Groundwater Prospects of Shahbad tehsil, Baran district, eastern Rajasthan: A remote sensing approach. *Journal of the Indian Society of Remote Sensing*, **25:** 239-246.

Saraf, A.K. and Choudhary, P.R., 1998. Integrated Remote Sensing and GIS Approach for Groundwater Exploration and Identification of Artificial Recharge Sites. *International Journal of Remote Sensing*. **19:** 1825-1841.

Shahid, S., Nath, S.K. and Roy, J., 2000. Grounwater Potential Modelling in a Soft Rock Area Using a GIS. *International Journal of Remote Sensing*, **21:** 1919-1924.

Singh, B., 1997. Water Resources Development in India—A perspective. *In:* Singhal, D.C. et al. (Eds.) Proceedings International Symposium on Emerging Trends in Hydrology, **I:** 1-17.

Singhal, B.B.S. and Gupta, R.P., 1999. *Applied Hydrogeology of Fractured Rocks*. Kluwer Academic Publishers, Dordrecht, The Netherlands. 324 pp.

Singhal, B.B.S. and Verma, O.P. (Eds.), 2003. S & T Inputs for Water Resources Management. Indian Geological Congress, Roorkee. DST's Spl. Vol. 3, 232 pp.