Groundwater Dynamics
in Hard Rock Aquifers

Groundwater Dynamics in Hard Rock Aquifers

Sustainable Management and Optimal Monitoring Network Design

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Cover illustration: Typical dug well in granitic hard rock terrain at Maheshwaram, Andhra Pradesh. Photograph taken by Dr. Shakeel Ahmed.

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Preface

Groundwater is of utmost importance in the arid and semi-arid environment. The areas in such regions are forced to face a variety of problems regarding groundwater as it is the main source of water no matter for any use viz., drinking, domestic, irrigation or industrial particularly for the rural population. The main challenges in hard rock areas in the semi-arid region are the water conservation, management and planning of the water resources. This is further complicated with several complexities of the geological formation. With the semi-arid environment, complex geological settings and over shooting stresses, the aquifer system becomes extremely fragile and sensitive. In spite of a good amount of research in this field, it is still needed to understand the behaviour of such complex system precisely and also apply the result in reasonably larger scales. Therefore, the present research is focused on improving the knowledge on the structure and functioning of the aquifer system in hard rock terrain.

An Indo-French Centre for Groundwater Research (IFCGR: www.ifcgr.net) set-up at the National Geophysical Research Institute (NGRI: www.ngri.org.in) in collaboration with Bureau de Recherche Géologiques et Minières (BRGM: www.brgm.fr), France has realized the need and set goal to study the hard rock aquifers for the groundwater flow and management particularly at local to medium scale. The centre has developed specific methods to:

- determine the geometry and extent of aquifers,
- estimate aquifer parameters and characterize the aquifer system,
- estimate recharge and irrigation returns as input to the aquifer system,
- estimate various parameters at the unmeasured locations and optimal monitoring network design,
- calculate the groundwater balance and simulate the groundwater flow and
- evolve the strategies for sustainable management of the ground water.

With a considerable amount of research and identifiable output, it was thought to share the findings and transfer the knowledge to other organizations and researchers in this field. The research work carried out by taking a pilot area on different aspects of groundwater management have been compiled and presented here in the book. A couple of state-of-the-art papers were included and the gaps were filled by adding a few more articles of relevance. Publication of this book will add value to the present readings in the subject and complete a milestone in the hard rock hydrogeology. The book starts with a couple of general articles introducing the IHP of UNESCO and water scenarios in India and then the basic knowledge on the hard rock hydrogeology as well as an overview of the work carried out at the Indo-French Centre for Groundwater Research, Hyderabad. The later articles are all technical depicting mostly the case studies on hydrodynamics of the hard rock aquifers with a brief theory on the applications of geostatistical methods as well as Aquifer Modelling.

The editors extend their sincere thanks to all the contributors and IFCPAR, New Delhi as well as UNESCO who have provided funding for the research projects whose results are embedded here. Editors are thankful to Prof. G. de Marsily, Ex-professor of Hydrogeology at the University of Pierre and Marie Curie, Paris, France for critically reviewing the book.

Shakeel Ahmed
Ramaswamy Jayakumar
Abdin Salih

An Introduction to UNESCO's International Hydrological Programme

Abdin Salih*

The United Nations Organization for Education, Science, and Culture (UNESCO) established International Hydrological Programme (IHP) in 1975, as the single intergovernmental programme of the UN system devoted to scientific study of the hydrological cycle and to formulating strategies and policy for the sustainable management of water resources.

IHP was conceived as an evolving programme, ready to adapt to society's needs and transformations. The Programme is implemented in phases of six years, in order to remain prompt in identifying new, emerging problems, alerting decision makers, raising public awareness and providing the necessary resources to respond with action.

The first phase, IHP-I, lasted from 1975 to 1980. IHP-II, on the other hand, was of a shorter duration (1981-1983). This was to enable the Programme to fit in with the timing of the Medium Term Plan of UNESCO.

IHP-I was mainly research-oriented following the International Hydrological Decade. However, in response to the concerns of Member States, the next phases were oriented to include practical aspects of hydrology and water resources. Hence IHP-II (1981-1983) and IHP-III (1984-1989) were planned under the theme Hydrology and the Scientific Bases for Rational Water Resources Management. The theme chosen for IHP-IV (1990-1995) was: "Hydrology and Water Resources Sustainable Development in a Changing Environment". IHP-V (1996-2001) was devoted to the theme: "Hydrology and Water Resources Development in a Vulnerable Environment".

In the development of its various phases, IHP has gone through a profound transformation from a single discipline to a multi-disciplinary programme. Recently, with the increased presence of the social science component, IHP has become a truly inter-disciplinary programme, capitalizing on the recognition that the solution of the world water problems is not just a technical issue.

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UNESCO's intergovernmental scientific cooperative programme in hydrology and water resources is presently the only broadly based science programme of the UN system in this area. It was established because both the international scientific community and governments, realizing that water resources are often the primary limiting factors for the peaceful development in many regions and countries of the world, saw the need for an internationally coordinated scientific programme focusing on water. It has had a prime role as a catalyst in promoting cooperation in water science and water resources management.

Today, integrated water resources management poses scientific, technical, socioeconomic, cultural and ethical challenges. IHP is a multidisciplinary programme at the forefront of assuming these challenges. To this end, IHP is a prominent UNESCO vehicle for meeting the UN Millennium Goals.

The current phase of IHP, IHP-VI, covering the period 2002-2007, is devoted to "Water Interactions: Systems at Risk and Social Challenges". The sixth phase of IHP emphasizes societal aspects of water resources. However, this emphasis should not be interpreted as the replacement of the primary concern: to study the occurrence and distribution of water within the natural environment.

The incorporation of the social dimension underlines the need for improved, more efficient management of water resources and the more accurate knowledge of the hydrological cycle for better water resources assessment. So far, water has been managed in a fragmented way. Surface water and groundwater are considered separately in development activities without due recognition of their interdependence. Water resources in many places are still not managed in conjunction with land resources. Water supply schemes, eventually generating large amounts of waste water in consumer areas, are normally designed and built, especially in developing countries, without the required matching drainage networks and waste water treatment facilities. Quantity is generally managed separately from quality, as is water science and water policy. This fragmentation of approach also impedes coherent hydrological analyses at regional, continental and global scales.

IHP-VI (2002-2007) has been based on the fundamental principle that fresh water is as essential to sustainable development as it is to life and that water, beyond its geophysical, chemical, biological function in the hydrological cycle, has social, economic and environmental values that are inter-linked and mutually supportive.

The launching of IHP-VI coincides with the emergence of a profound paradigm shift in society's approach towards water. As far as the management of this resource is concerned, it is documented in the call for integrated water resources management. Research to support integrated water resources management should also be integrated. This implies not only more inter- and multi-disciplinary approaches but also more co-operation and partnership in executing research programmes. In this regard, water-related activities of intergovernmental organizations (IGOs) should co-operate and be co-ordinated with the programmes of non-governmental organizations (NGOs). It is expected that this synergy could be the most important basis to successfully implement IHP-VI.

In line with the above-mentioned comprehension of water interactions, technological development of data acquisition and improved modelling of processes and interactions, the relevant IHP-VI topics on hydrologic research, water resources management and education are framed under five themes. The transition and interaction from the global scale to the watershed scale being the overall driving force for the consideration of the complex relationships between water and society and the overall need for knowledge, information and technology transfer.

Theme 1 - Global Changes and Water Resources
Theme 2 - Integrated Watershed and Aquifer Dynamics
Theme 3 - Land Habitat Hydrology
Theme 4 - Water and Society
Theme 5 - Water Education and Training

Two crosscutting programme components: FRIEND (Flow Regimes for International Experimental and Network Data) and HELP (Hydrology for Environment, Life and Policy) have been identified that, through their operational concept, interact with all themes.

Besides the obvious symmetry with FRIEND, HELP is conceived to be funded entirely from extra-budgetary or external financial sources. This structure accounts first of all for the considerably higher financial requirement and longer time scale of HELP projects than for the ones in the regular IHP time and budget framework. However, it is fully considered as an integrated part of IHP-VI (and beyond) as far as scientific objectives, approach and result dissemination is concerned.

A pilot project on "Analyses of Geochemical Contamination in Groundwater including monitoring network design in hard rock aquifer systems" was taken up as part of IHP-VI Theme II - Integrated Watershed and Aquifer Dynamics, in collaboration with Indo-French Centre for Groundwater Research jointly sponsored by National Geophysical Research Institute, India and BRGM of France. Under this project a large number of experiments have been conducted to thoroughly investigate the area. The information gathered from the field has been interpreted by different methods to establish the best and suitable technique to be applied. Extensive application of aquifer modeling and geostatistics were made to make the study versatile. A few new techniques have developed particularly the geostatistical monitoring network design etc. A project on the groundwater management in this weathered-fractured aquifer has been completed and refining of the model with the additional data and for further research particularly unsaturated zones are continuing. I believe our collaboration with this centre will go a long way in implementing IHP priorities.

UNESCO and IFCGR is planning to create a network of scientists from Asian region and around the world on “Groundwater Monitoring Network Optimization for hard rock areas” to bring all the scientists working in this area together to create a monitoring network design which is the backbone of any development activities in the hard rock aquifer system. I hope through this initiative this region as well the whole world will be benefited in terms of groundwater monitoring in the hard rock aquifer systems.

World Water Assessment Programme is one of the recent initiatives of all UN Agencies in the field of water. This UN-wide programme seeks to develop the tools and skills needed to achieve a better understanding of those basic processes, management practices, and policies that will help improve the supply and quality of global freshwater resources. The United Nations system is complex. It is not easy to explain what each agency and programme does, since each one has its own priorities and procedures. Under this common banner, they have agreed to work together—sharing information, knowledge and know-how—to improve our understanding of the policies and practices that encourage sustainable use of water resources.

We in UNESCO-IHP have now started preparing the themes for IHP Phase VII (2008-2013), and the consultation with member states has started. I request all the scientists and engineers participating in this workshop to consult their respective IHP committees after this training to critically evaluate the priorities and proposals. The Task Force suggests the following four themes for IHP-VII:

Theme I: Global Changes, Watersheds and Aquifers
Theme II: Governance and Socio-Economics
Theme III: Water and Environmental Management
Theme IV: Water Quality, Human Health and Food Security

Finally, the challenge we all have is **“How to put water in the minds of people?”** Let us work together to solve the world’s most important problem of water in the coming years. Let me conclude my introduction with a quote from former President J. F. Kennedy **“Anybody who can solve the problems of water will be worthy of two Nobel Prizes, one for peace and one for science”.**

About the Editors

Dr. Shakeel Ahmed

Dr. Shakeel Ahmed (born 1958), basically a geophysicist from India, completed his higher studies at Paris School of Mines, France and obtained degrees of DEA and Doctorate as well as Diploma in Geostatistics. Presently serving as Deputy Director of National Geophysical Research Institute, Hyderabad, Dr. Ahmed started his research career by working on an advanced subject of aquifer modelling for groundwater management and geostatistics as well.

He is presently heading the Indian team at the Indo-French Centre for Groundwater Research (IFCGR), an advanced research centre (www.ifcgr.net) where scientists of NGRI, India and BRGM, France are committed for research in hard rock hydrogeology. With about 50 research papers in various journals and many proceedings to his credit, he has edited five published proceedings of international conferences.

Dr. Ahmed is recipient of the Young Scientist Award in physical sciences for the year 1996 from MAAS as well as International Prize of Water Sciences of 2004 awarded by the Cannes Water Symposium, France. He has served as elected secretary of the Indian National Committee of the International Association of Hydrogeologists for about 10 years. Dr. Ahmed is presently associate editor of the *Hydrogeology* journal and member of the editorial board of International Journal of Chemical and Environmental Research.

Dr. Ramaswamy Jayakumar

Dr. R. Jayakumar has obtained Ph.D. in Hydrogeology with post-doctoral experience in conjunctive use of surface and ground water for irrigation. He has specialised in application of remote sensing, GIS and geo-statistics in hydrogeological modelling with a special training in related fields from Osaka City University, Japan. Having worked for the UNESCO, New Delhi, looking after hydrology, and coastal and small islands programmes, he served as a Hydrogeologist with Ford Foundation Project in Anna University, Chennai and later with WS Atkins International Limited, Cambridge, UK in Irrigation Projects funded by Commission of European Communities. At present he is working in UNESCO Beijing office, P.R. China, looking after the Science and Technology programme of UNESCO.

Dr. Abdin Salih

Dr. Abdin Salih, obtained his Ph.D from the Imperial College of Science and Technology, University of London (U.K), 1972. His field of interest is environmental sciences, particularly hydrology (including groundwater), hydraulics, and water/land resources management under arid conditions.

He has worked extensively in renowned universities like University of Padova, Italy; Colorado State University, USA and King Saudi University in Riyadh. He has served as an advisor in many large national water and environmental research projects.

Dr. Salih is a serving member of UNESCO's Advisory Board of the Great–Man-Made River of Libya (1990 to date); and led a multidisciplinary team in 1986-1990 to study and solve the engineering and environmental problems related to the rising groundwater beneath the City of Riyadh (Saudi Arabia). He has contributed over 75 papers and chapters in books, various journals and proceedings of referred conferences and prepared over 30 technical reports. He has served in the editorial board of many national and international journals.

One of his major achievements is the establishment of considerable visibility and remarkable respectability to UNESCO's International Hydrological Programme (IHP) and to its Man and the Biosphere (MAB) programme. Since June 1999 till date, he has been serving as Deputy Secretary of the IHP at UNESCO's Headquarters in Paris. In this capacity, he participated in the shaping of the phase six of IHP (2002-2007) and contributed to many new initiatives, including the UN-wide World Water Assessment Programme, the establishment of the IHE of Delft as a UNESCO-IHE Institute of Water Education, and the Regional Centres in Cairo, Tehran and Chile. He has also been instrumental in securing extra-budgetary contributions to IHP, particularly the over $2.3 millions Flanders Fund in Trust Support to FRIEND/Nile, Palestinian Territories, South Africa and Chile projects. Since January 2003 he continues to hold the post of Director of UNESCO Tehran Office.

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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.

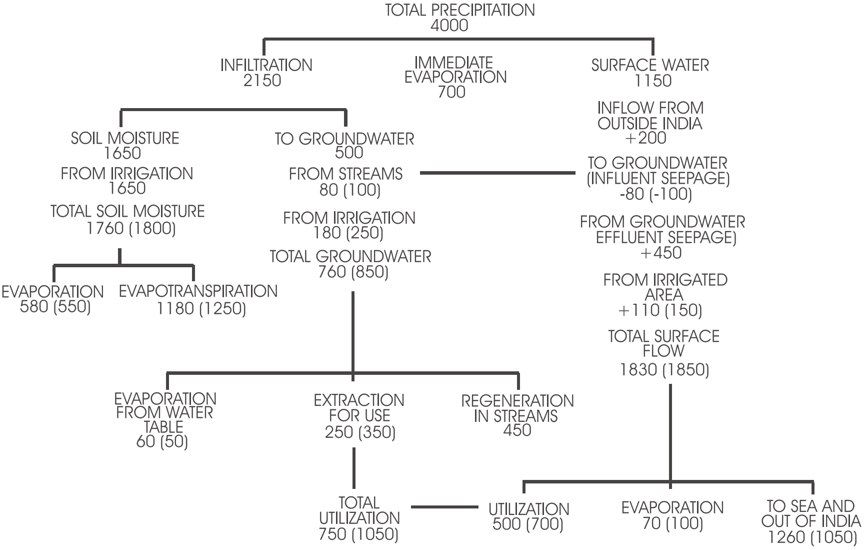


Figure 1. Approximate annual water resources of India in 2000 and 2025 AD (in km^3). The values in brackets are those anticipated for 2025 AD (Singh, 1997).

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

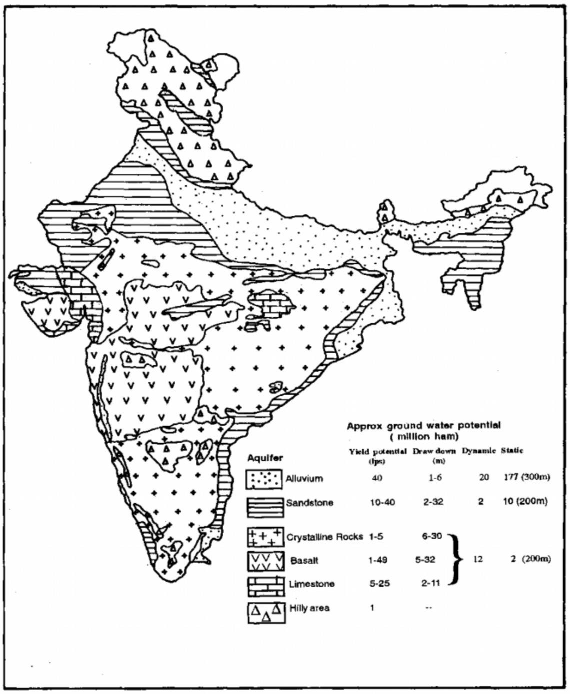
Sl. No.	*Name of Basin*	*Total Replenishable Ground Water Resources (km^3)*
1.	Brahmai with Baitarni	4.05
2.	Brahmaputra	26.55
3.	Cambai Composite	7.19
4.	Cauvery	12.30
5.	Ganga	170.99
6.	Godavari	40.65
7.	Indus	26.49
8.	Krishna	26.41
9.	Kutch and Saurashtra Composite	11.23
10.	Madras and South Tamil 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.



Aquifer	Yield potential (lps)	Draw down (m)	Approx ground water potential (million ham) Dynamic	Approx ground water potential (million ham) Static
Alluvium	40	1-6	20	177 (300m)
Sandstone	10-40	2-32	2	10 (200m)
Crystalline Rocks	1-5	6-30	12	2 (200m)
Basalt	1-49	5-32		
Limestone	5-25	2-11		
Hilly area	1	--		

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 1.6×1.0^{-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.