A REVIEW ON
CSIR-NGRI'S CONTRIBUTION TO HYDROLOGY ON GLOBAL AND INDIAN SCENARIOS

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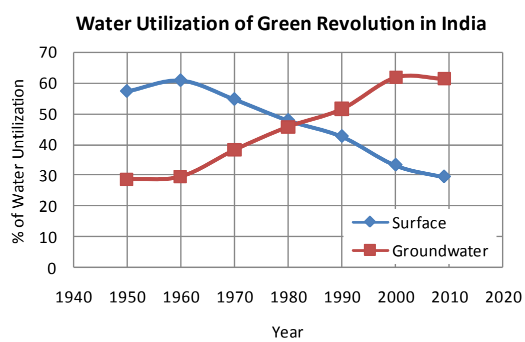
The review is categorized into three parts i.e. (i) major challenges on groundwater in India; (ii) overall CSIR-NGRI's contribution to the hydrology; and (iii) what and how CSIR-NGRI can play role towards achieving sustainability of groundwater resources with special reference to Dehradun declaration.

1. MAJOR GROUNDWATER CHALLENGES

The mankind has entered the 21st century with a gloomy picture of fresh water source of the world. Today, these water resources are under unprecedented stress due to excessive and usually irresponsible usage. Large aquifers with negligible recharge are being mined for the past several decades (Gorelick and Zheng, 2015) resulting into water crisis (Zheng and Liu, 2013); 21 out of 37 major aquifers in the world are facing groundwater depletion at alarming rates. As per UNEP report in 1990-93, India is recognized as world's highest land under irrigation, at 50.1 m ha, which consumed 460 BCM water, of which 41% came from surface water and 53% from groundwater. During 1950 - 1985, surface water irrigated land doubled, but the aquifer based irrigation has increased by 113 times. Thus role of aquifers to hydrological cycle of storing and subsequently releasing water has been increased significantly over the past 60 years (Fig.1). The aquifer water thus plays two major roles i.e. (i) supporting environment by maintaining and sustaining land greeneries, springs, wetlands and river flows; (ii) essential need of water to the industry, society and crop irrigation. Thus the over utilization of groundwater has led to a crisis situation. The water security in India is widely recognized as one of the major challenges to the nation's economy and social development (Brisok and Malik, 2005, GOI, 2009). The growing dependency on groundwater and its escalating demand has resulted into regional dwindling of the groundwater resources and drying up of entire aquifer systems (Tiwari et al., 2009). Various groundwater management programs carried out for the past few decades in India by the several implementing agencies such as Central and State Departments as well as NGO's have proved futile in sustaining the precious resource.



There have been and even upcoming programs such as preparing artificial recharge structures, check dams, de-siltification of tanks, smart city development, selecting land fill sites, etc, which are done on the ground. However, the knowledge of the subsurface lithology is majorly ignored. Though there are many challenges, three major challenges are listed below:

1.1 Groundwater over-exploitation and expanding water crisis zones

Groundwater crisis is one of the most challenging problem globally as well as in India. Many parts of the country face acute shortage of the water, the boreholes go dry during the peak summers. As per the WRI Report (2015), 54% of India faces high to extremely high water stress. Decline in the water table is also affecting the deterioration in the water quality. More than 100 Million people live in areas with poor water quality. A comparison with the groundwater abstraction trends for India, USA and China for the period 1950 to 2050 shows that while USA and China have been successful in checking the abstraction of their groundwater resources, India's abstraction is

increasing without any check, running parallel to the growth of its population. India is going to face a disastrous groundwater situation if the necessary measure is not taken.

1.2 Deterioration in groundwater quality such as Arsenic & Fluoride contamination, Industrial Pollution and sea water intrusion, etc

Groundwater contamination is increasing day by day due to natural and anthropogenic activities. A large part of the population is exposed to variety of chemicals in the industrialized world. The disposal coming out of the industries contains many toxic metals hazardous to health. Both the arsenic and fluoride occur from geogenic and anthropogenic sources in groundwater. The Arsenic contamination is found increasing at alarming rate. Initially it was reported in Bangladesh in 1995, but subsequently, spread in adjacent areas such as West Bengal followed by many patches in Lower, Middle and upper Ganga Plains (Acharyya and Shah, 2007; Chandra et al., 2011). Bangladesh started exploiting deep aquifers to avoid contaminated shallow aquifers without having knowledge of lithological setup, which has induced vertical leakages of contamination from shallow to deep aquifers.

1.3 Desertification and waterlogging / swamping

Around 10,000 years ago, the western Rajasthan was the green and fertile belt due to-mighty river flowing down from Himalaya. It is a well known fact that Indian civilization prospered around the riverbank of Saraswati in the northwestern India. The huge amount of water running through the river and rainwater were abundant to provide ample sustenance for the agricultural activities. The tectonic disturbances, around 1.7 my ago in the Siwalik domain, converted perennial Saraswati River into a non-perennial one dependent on monsoon. The Saraswati had tributaries like: Satluj, Ghaggar, Drashdavati, Yamuna, Vyas, etc. Due to neo-tectonic disturbances in the Siwalik Himalayas, the water flow in to the River Saraswati was blocked and most of the water got diverted in to the River Yamuna. With the decline and disappearance of Saraswati, the ancient civilizations, that it supported, also faded (Sankaran, 1997). Finally the green belt turned into desert over the period of time.

In contrast to water resource shortage and resultant decline in groundwater level in different parts of Rajasthan, Jodhpur faces alarming situation of rapid rise in groundwater level. The waterlogging problem started after the city started getting water from Rajiv Gandhi lift canal since 1998. It is understood that there must be a large network of sub tributaries to Saraswati River spread in different parts. However, the lack of knowledge of these networks is one of the main weaknesses in making any sustainable plan.

2. OVER VIEW ON SCIENTIFIC CONTRIBUTION AND ACHIEVEMENTS OF CSIR-NGRI TO INDUSTRY AND SOCIETY

2.1 Groundwater Geophysics

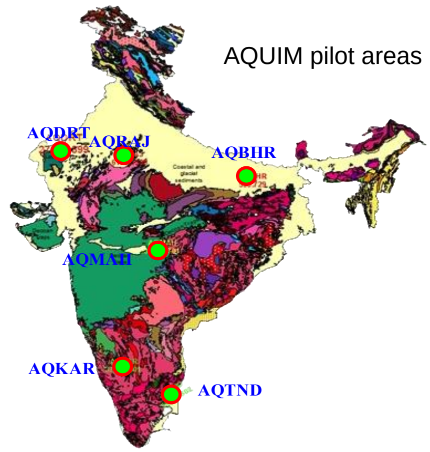
The CSIR-NGRI has played significant role in strengthening the geophysical techniques and developed various methodologies used for groundwater exploration, assessment and management over the past 50 years. The institute has theoretical and applied setup to give a complete solution to the industries and Society. DC electrical resistivity method has been one of the most applied techniques in the field of hydrology. CSIR-NGRI has studied efficacy of various electrode arrays viz., Wenner, Schlumberger, unipole, two-electrode, pole-pole methods, dipole (equatorial, radial, parallel), laterolog, etc., over the different targets using the physical laboratory model study and prepared nomogram (Apparao et al. 1978). Roy and Apparao (1971) have introduced a original concept of depth of investigation (DOI) that measure of depth to the zone contributing maximum to the signal measured at the surface in the DC method. The geophysical community has used this concept worldwide. Of course, there have been several additional new and modified concepts on DOI introduced across the various geophysical techniques. For example, Edward (1977) has suggested a modified DOI and called as Median Depth of Investigation. The DOI concept has been used even in the latest development of electrical resistivity tomography, which gives 2D and 3D resistivity structure of the subsurface. In 1980, Das and Verma developed digital linear filter for computing type curves for the two-electrode system of resistivity sounding and a theory for Bipole-dipole method of resistivity sounding as well as generalized computer program to compute the type curves of different DC arrays using digital linear filters.

In 1993, a new approach of Cokriged Estimation of Aquifer Transmissivity was introduced as an Indirect solution of inverse problem (Ahmed and G. de Marsily, 1993). Aquifer transmissivity is one of the important inputs to the groundwater modeling. In 2007, CSIR-NGRI based IFCGR developed a decision support tool with variable agro-climatic scenarios for sustainable Groundwater Management in semi-arid hard rock areas. This facilitates simulating the groundwater resource evolution for different scenarios, viz. changing cropping patterns, artificial recharge, climatic conditions, etc. The simulation result is dependent on the accuracy of the required hydrogeological inputs such as aquifer thickness and specific yield variations with depth in addition to rainfall, land use, water level time series, etc. In hard rock aquifers, flow is mainly constrained by discrete fractures or fractured zones (Dewandel et al. 2007). This has been transferred to the then AP State Groundwater and Rural Departments in 2008. CSIR-NGRI has contributed to the society under Rajiv Gandhi Drinking Water Mission where large number borehole sites were provided using geophysical surceys and drilled towards supplying of water for drinking and domestic needs.

For an effective groundwater management plan it is very important to carryout precise groundwater budgeting, which is highly dependent on the input parameter to the groundwater model such as hydraulic conductivity, natural recharge, boundary condition, aquifer disposition, etc. Chandra et al (2008) coupled Darcy's Laws of groundwater flow and Ohm's law of current flow based on the analogy on their flow pattern and established methodology for estimation of hard rock aquifers hydraulic conductivity from geoelectrical parameters. In 2011, CSIR-NGRI has also established a method called lithologically constrained rainfall (LCR) for estimating spatio-temporal distribution of natural recharge in hard rock terrains (Chandra et al., 2011). Over-compartmentalization of the hard rock aquifer system due to high spatial variability in fractured hard rock system was established. In such situations lineament plays an important role in understanding the hard rock hydrodynamics. Chandra et al (2006) revealed that the lineament need not to be always potential or non potential to the groundwater. They have demonstrated that the geophysical characterization helps in understanding their groundwater potentiality. Chandra et al (2010) carried out geophysical modeling of geological discontinuities with special reference to the groundwater occurrences. Although quartz reef and dolerite dyke both are intrusive in granite host rock, they have contrasting characteristics in weathering and fracturing leading to ~~a~~ different roles for groundwater dynamics. The weathering/ fracturing were limited to $\sim$ 8 m in the granite, whereas it is found up to 85 m deep in quartz reef.

CSIR-NGRI has taken a burning problem of managing groundwater resources in arsenic contaminated Middle Ganga Plain under CSIR groundwater network project under 11th five year plan. There have been number of studies mostly dealing with geochemical aspects of the contamination and designing of various filters for removal of arsenic (Shen, 1973; Shih, 2005). The sludge coming out of the filter became a matter of great concern as it goes again into the subsurface and add contamination of groundwater regime in the surroundings. In order to achieve sustainable solution, CSIR-NGRI has carried out a detailed study in MGP and shown that subsurface lithology controls the arsenic contamination in groundwater. The knowledge of the clay barrier is very important for the policy makers to plan habitation of the people in order to avoid arsenic contaminated water for drinking purposes. The results on one hand provided an insight into the process of Arsenic contamination, on the other hand depicted the aquifer set up that helps separating and safeguarding the zones free from contamination in the multi-aquifer system existing in the MGP, India.

In all the above studies, it is evident that unless and until we have a high-resolution knowledge base of near surface including vadose zone and aquifer system in three-dimension, an effective management of groundwater resources may not be possible. In order to achieve this objective CSIR-NGRI has recently worked on "**Discovering and Mapping aquifers to meet India's water challenges using advanced geophysical technique".**



An emerging approach increasingly utilized world over is to achieve continuous regional-scale aquifer mapping employing heliborne geophysical measurements, and integrate the ensuing results with the geological and hydrogeological data to reliably characterize the aquifers. CSIR-NGRI has successfully carried out state-of-the-art heliborne transient electromagnetic investigation first time in India for aquifer mapping obtaining fascinating results on the aquifer systems and their spatial characteristics covering almost all types of geological formations present in the country (Ahmed, 2014; Rao et al., 2015). Figure shows six pilot survey areas located in divergent hydrogeological terrains. The results, in general, helped in mapping the aquifers in 3 dimensions in desert, alluvium, hard rocks, sub-basaltic and coastal tracts. The major outcome of the project could be listed as:

(i) Mapped fracture network in hard rock terrains;
(ii) Mapped Deccan basaltic flows and Basalt-Gondwana Contact with aquifer potential;
(iii) High-resolution maps of Palaeo channel & palaeo coast
(iv) Extent of in-land salinity in Coastal zones
(v) Aquifer below saline bed in desert
(vi) Clays lenses separating aquifer in MGP

Besides, it helped constructing the concealed subsurface spatial disposition of structures controlling the groundwater dynamics. CSIR-NGRI has taken lead in the country in setting up a road map for fast and high-resolution aquifer mapping using heliborne geophysical investigations. This provides an essential base for making any plans on the land for effective and realistic groundwater management, smart city development, selecting potential groundwater site, making artificial recharge structure, siting for land dump fill site, etc. Ultimately a national aquifer grid can be prepared for use of the society as well as the planners.

2.2 Isotope Hydrology

Isotope hydrology lab at NGRI is functioning continuously for last 40 years carrying out groundwater carbon-14 (^{14}C) dating from different geological environs of India. In the coastal regions, isotopic and hydrochemical signatures in the groundwater indicated its potential for exploitation and ill effects due to over exploitation (Sukhija et al., 1989a, b; Reddy et al., 2014). Organic biomarkers along with ^{14}C dating were used to distinguish the in-situ salinity and seawater ingression in coastal aquifers (Sukhija et al., 1996a). Extensive groundwater dating in the Nyveli lignite mine area (Tamil Nadu) was used to identify the principal recharge and discharge areas, groundwater flow direction and flow rate for highly potential deep confined aquifer. Evaluation of direct recharge to the aquifer (Sukhija et al., 1996b) from rainfall and identification of hydrological changes occurring in the aquifer due to continued heavy withdrawal of groundwater for lignite mining (Sukhija et al., 1996c), enabled the personnel associated with mining activity to assess the impending implications pertaining to changed hydrologic regimes and sea water intrusion. Further, the ^{14}C dates of this groundwater were interpreted in terms of the paleo-climatic conditions of this area (Sukhija et al., 1998).

A study on "Source of seepage water in Sudamdih mine area (Bihar) using the environmental isotopes" identified the source of seepage thereby helping the authorities to continue the mining activity (Sukhija et al., 1987). A study to trace-out the water path of injected water for secondary recovery of oil in the Nawagam Oil Field (Gujarat) using isotopic and hydrochemical characters of injected water, was useful to establish the directions of pre-mature breakthrough from permeable paths from the injection wells. This methodology has been granted patent (IPMD No. 0209NF 2004) in US, GB, CA, RU, MX, NG countries. ^{14}C dating of deep groundwaters from Jaisalmer area (Rajasthan) as part of efforts to trace the Saraswati River yielded as old as >45 ka BP, much older than the believed age of this river (Reddy et al., 2010a). Hydrochemical and isotopic measurements of Tural hot spring water in the Western Ghats, indicated about 3 k years of circulation time through underlying granitic basement (Reddy et al., 2013). Highly alkaline and saline inland Lonar Lake of one km^2 is part of the Lonar Crater situated in Buldhana dist. of Maharashtra. Of late, it is reported that the alkalinity and salinity of the lake water is being diluted with increased lake water level due to external inputs like seepage of water in to the lake from nearby surface reservoirs being used for agriculture. A public litigation case was filed to close the irrigation tank. Studies on hydrochemical and isotopic signatures of lake water, and also lake water levels showed that, the water level and the hydrochemistry of lake water are controlled by the local rainfall and evaporation, and that there are no other external water inputs to the lake (Reddy et al., 2015a).

First time in India, Environmental tritium was used to determine the natural rainfall recharge and meaningful recharge estimates were made for alluvial tracts of Gujarat (Sukhija and Shah 1976). Further, the study was extended to other areas. As environmental tritium measurements needs sophisticated instrumentation, an alternate, cheap and more reliable Environmental Chloride Method (ECM) was developed (Sukhija et al 1988), tested in different geological environs. Further, based on this method, significant contribution from the preferential flow recharge in the fractured and hard rock terrains was demonstrated (Sukhija et al., 1996d; Sukhija et al., 2000; Reddy et al., 2009). Apart from natural recharge estimation, the chloride mass balance (CMB) method was developed to assess the performance of percolation tanks (Sukhija et al., 1997) and applied in different geological terrains of India (Sukhija et al., 2005). The method has also been granted patent (IPMD No. 0349NF-2004) in US, AU, NZ, ZA countries.

Using isotopic and hydrochemical parameters, a study on “source of pollution at Tirumala-Tirupati Devasthanam (TTD), A.P., India” led to evacuation of choultries around the temple, which were responsible for pollution (Sukhija et al., 1989c). This also led to beautification of temple surroundings. Detailed investigations in the fluoride (F) affected areas of Nalgonda dist (Telangana) helped in understanding the sources and mechanism for high F in groundwater (Reddy et al., 2011a). Studies on possible sources of nitrate pollution in groundwaters of different areas shows village environs are more potential sources than agriculture activity (Reddy et al., 2010b, 2015b). Hydrochemical studies in the Chronic Kidney Diseases affected areas (Srikakulam and Prakasam dist. Of AP) clarified that drinking of local groundwater (Reddy and Gunasekar, 2013) is not causing the disease. Towards development of new tools for identification of potential fractures in hard rocks, soil gas radon emanometry was used as a geochemical tool in deciphering groundwater potential fractures (Reddy et al., 1996, 2006).

Earthquake precursory investigation using hydrochemical/isotopic changes in the deep groundwater is being carried out in the Reservoir Induced Seismic zone of Koyna (Maharastra) since January 2005. Based on changes observed during M 5.1 earthquake on 14th March 2005 (Reddy et al., 2011), and subsequent changes after the earthquake, probable period of impending earthquake was estimated and it was realized within the estimated period (Reddy and Nagabhushanam, 2011, 2012). Further, ^{14}C dates in association with stable isotopes and hydrochemical data helped to understand the hydraulic linkage between the Koyna – Warna reservoirs (believed to be responsible for induced seismicity) and surrounding groundwater up to the depth of 200 m (Reddy & Nagabhushanam, 2015).

2.3 Aquifer Recharge

CSIR-NGRI has also a dedicated team on aquifer recharge with significant contribution from available techniques on geochemical, tracer and rainwater harvesting applied to quantifying aquifer parameters, specific hyrogeological investigations for groundwater exploration and development of management strategies for quality improvement, safe drinking water supply and aquifer sustainability (Athavale et al., 1983; 1992 & 1998; Rangarajan and Athavale, 2000). Following are the type of activities, broad results and significant achievements.

i) Dynamic groundwater resource potential in major river basins of India

Injected tritium tracer technique was used for natural recharge measurements in 55 watersheds / river basins / administrative areas in India during the last 40 years. Natural recharge data indicates that only 8-10 % of recharge occurs in hard rock terrains such as granites and basalts and 12-15 % in sedimentary and alluvium formations. The data obtained were used for establishing rainfall-recharge relationship for major hydro geological provinces of India such as granites, basalts, sediments and alluvium. The relationships obtained were used for estimating natural recharge quantum for 17 major river basins of India. The total annual replenishable ground water potential of India, for normal monsoon year is calculated as 476 km^3.

ii) Demarcation of recharge area to confined aquifers of Neyveli groundwater basin, Tamilnadu. This helped for planning ground water control operation for safe open cast mining of lignite deposit in Neyveli, Tamil Nadu

iii) Moisture movement mechanism in desert soils

Injected tracer technique was used for quantifying influx and efflux of moisture in desert soil caused by rainfall. The experimental study has indicated about 68% of the total moisture entering a desert soil is returned to atmosphere and the moisture loss is mostly through the process of vapour diffusion.

iv) Detecting subsurface Chromium contamination in Vellore district, Tamil Nadu

Hydrogeological, geophysical and tracer techniques were used to detect subsurface chromium contamination, ground water flow pattern and selection of waste disposal site in Ranipet, Vellore district, Tamil Nadu. The integrated studies and construction of waste disposal site based on NGRI recommendation has controlled the chromium contamination to groundwater resources.

v) Established dydraulic connectivity of subsurface geological structures (dolerite dyke) in Rangareddy district, Telangana, which facilitates ground water movement and thus pollute the drinking water source located nearby by oil based industry. Based on the findings, the authority has asked the oil based company to shift their production unit elsewhere.

vi)_Helped BARC to identifying the source of radioactive contamination using our established ground water flow pattern through integrated study. This has been done in 3 nuclear power plant sites i.e. Kalpakkam in Tamil Nadu, Kakrapar in Gujarat and Tarapur in Maharashtra.

vii) Bore hole tracer technique for studying fracture flow

Experimental investigations were carried out in Manikaran hot water spring area for studying flow of thermal water through fractures and in hard rock watersheds. The case studies collectively highlighted the utility of tracers for understanding the groundwater flow over fractured system and paved a way to augment the groundwater resource for source sustainability.

viii) Rainwater harvesting and artificial recharges technologies

Application of rain water harvesting, artificial recharge techniques and water conservation strategies were successfully implemented in achieving aquifer sustainability for irrigation, potable source water creation, sustainable rural potable drinking water supply, fluoride reduction in groundwater and also used available scientific techniques for assessing the impact of strategies / structures implemented.

3. WHAT AND HOW CSIR-NGRI CAN PLAY ROLE OF CATALYTIC AGENT TO EVOLVE INDIA INTO SAMARTH BHARAT- SASHAKT BHARAT.

CSIR-NGRI has acquired world-class large-scale data in major hydrogeological setup of the country for the past three years, which need to be used to bring out translational research benefitting the industry and society. The project was done with the set project objective. However, it can bring out many breakthrough results. R&D objectives of the project could be:

a. Establishing methodology for translating large scale dense geophysical data into lithological and hydrogeological parameters and prepare 3D litho-structural map of aquifer systems in different geological environs; establish their geometry as well as extent.
b. Establish hydrological and geological compartmentations of aquifer to understand a realistic flow regime and contaminant distribution as well as linkages among the aquifers.
c. Develop methodologies for estimation of hitherto ignored system fluxes; accurate estimation of important flux to provide a realistic water balance.
d. Develop Decision Support Tool at various scales for sustainable groundwater management under changing scenarios.

Integrating various geophysical data sets become important to reduce geophysical inherent ambiguities and translating the integrated geophysical data into hydrogeological model in semi-automated mode will facilitate to cope up with large-scale data, which otherwise may be time consuming process in a manual mode. Methodologies to assess various fluxes of the groundwater system also need revision and the processes as well as the medium through which they take place are to be viewed in the light of the advanced developments and techniques. This will allow estimating various fluxes of the system accurately and an effective water management at different spatio-temporal scales. The new tool based on the complete knowledge generated and with use of process-based estimations, will produce the predictive results and satisfy the water users. The application of several advanced techniques and minimization in uncertainties of estimates will provide utmost confidence among water users and that will also lead to evolve implementable groundwater legislations as a need for the country. Ultimately CSIR-NGRI should be able to provide a complete and sustainable solution incorporating all the major variables through the pilot study and provide road map to the implementing agencies such as central and state groundwater departments and NGO's to upscale at the country scale in order to meet nation's mandate on Make in India, Smart City Development and finally play a role of catalytic agent to evolve India into Samarth Bharat-Sashakt Bharat.

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