INTRODUCTION: Widely varied Groundwater Situation

Ancients knew about groundwater and its use. Large diameter open wells, step wells or similar structures served them for drinking water and other uses in rain deficient periods. It is since mid-sixties that groundwater exploitation supported by hydrogeological surveys and exploration was launched in a big way and stepped up with time to meet irrigation and drinking water needs. The information accrued through studies over the last seventy years are depicted in Hydrogeological map of India (1:5 &1:2 million) bringing to the fore widely variable hydrogeological condition in the country and gives a glimpse of the management issues (Fig.1).

Broadly two main hydrogeological zones are recognized in the country.

1. The Indo-Ganga-Brahmaputra plains, and coastal alluvial basins endowed with regionally extensive, thick, high yielding aquifers (25->50 lps) and intensively developed. But groundwater potentials drop sharply north westwards in the arid and semi-arid climate. Unconsolidated and porous alluvial sand and gravel layers constitute aquifers under unconfined or confined conditions. In the coastal alluvial basins aquifers are beset with salinity hazards. Here the issue is balanced development without overexploitation and hydrochemical equilibrium.

2. The Peninsular shield, composed of consolidated hard formations with semi-consolidated Gondwana sedimentaries in rift basins. A substantial part of the terrain is in arid, semi-arid and drought prone areas. Weathered and fractured rocks form aquifers thin, discontinuous with moderate to low yield (<1 to 25 lps). Here the issue is locating and delineating the unevenly distributed water saturated zones, and their sustained yield. Hydrogeological conditions depend upon rainfall, topography, soil, lithology and structure. But lack of adequate knowledge of sub-surface geology, structure and hydrology is a major hindrance in resource management. The following are some of the hot spots in Indian hydrogeology.

HARD ROCK AQUIFERS: Unpredictable Success of Well Drilling

A wide variety of rock types of different ages constitute the hard rocks, namely granites, gneisses, schists, amphibolites, phyllites, granulites, ultrabasics, intrusives, metamorphics, charnockites, khondalites, sandstones, quartzites, slates, limestones, collectively known as basement complex; and trappen basalts.

Basement complex: Granites and granite gneisses form the most potential aquifers. These are consolidated formations with primary porosity weeded out through metamorphism, induration and tectonic deformation in the geological past, but rendered porous through weathering, fissuring and fracturing forming aquifers. Fracturing may occur in several phases of tectonic deformation (Fig.2). Long deep seated vertical to sub-vertical, narrow fracture zones are the results of ruptrual deformation. Open tensile fractures persisting over long distances act as potential groundwater reservoir. Usually the younger set of fractures are more productive than the other sets. The fractures originally developed as tensile and open, later might become shears on compression. A hydraulic continuity exists between weathered zone and underlying fractured zone. Interconnected fracture systems of two different phases of deformation may form one hydraulic system.

Fig.1. Hydrogeological map of India. (source: CGWB).

Fig.2. Ruptural deformation history in hard rocks of Kerala (Report, SIDA assisted coastal Kerala Groundwater Project, 1992).
Because of the heterogeneity of fracture distribution, interconnectivity of different fracture systems and weathered residuum, fracture spacing and aperture size which together determine fracture permeability and porosity, groundwater flow through fracture systems in hard rocks is complex. The flow mechanism is different in early, intermediate and later time of pumping as studied in Thrissur, Kerala (Kukilaya, 2008, Geol Soc. Mem. 67). Aquifers are thin, unevenly distributed, and their yields fluctuate widely within short distances. Unconfined to semi-confined condition prevails down to a depth of 100m. The average specific yield values of weathered/fractured granitic rocks and the storativity values of deeper aquifers are generally of the order of 0.4-3.0 and $10^{-3}$-$10^{-4}$ respectively (Karanth, Sem. IAH, 1986). There is also sharp decline in aquifer productivity below this depth due to fractures being tight and less frequent.

Thus, drilling a successful bore well is riddled with uncertainty. Space technology, GIS, geophysics and flow modeling may solve some of the riddles of fractured rock aquifers.

**Deccan traps:** The Deccan traps present a more complex hydrogeological scenario. In the classical concept the trappean aquifer system is simulated to the Snake Valley model in USA comprising a layered complex. Each flow has a top vesicular layer, followed by massive jointed and fractured layer with a vesicular bottom. The flow layers are characterized by primary porosity in the vesicular layer and secondary porosity in fractures and joints, the storativity and transmissivity being in the ranges of 0.8-2.9/80-503 m$^2$/day, and 0.6-2.9/26-450 m$^3$/day respectively. Compared to the basement complex the trappean aquifers yield less which too varies widely and unpredictably. In search of more viable models which may explain the heterogeneities better, following Hawaiian nomenclature Deccan traps have also been subdivided into “compound pahoehoe flow, typically hummocky and sheet flow type with sheets showing an upper vesicular zone (crust), followed by non-vesicular core/zone; and a lower vesicular zone (basal zone)” and “simple aa type flows, fairly thick, broad flow fronts, nearly flat upper surface capped by discontinuous flow top breccia”. Duraiswami and others (Geol. Soc. India, Mem., 80, 2012, pp.12-13) feel that internal morphology and structure of the basaltic subunits. Sheet joints contribute groundwater occurrence in basaltic aquifers, its development and conservation. Recoverable ground-water is confined to vesicular crust and or jointed core. Hydraulic conductivity between these zones and shallow soil/alluvial aquifer determine potentiality of the aquifer. Several combinations of morphogenetic models have been proposed to conceptualize groundwater flow domain. Scenarios ‘4’ above ‘3’ in Fig.3 is the most viable combination, as corroborated by efficient water conservation structures in Raleygaon Sidhi in Maharashtra:

(3) **Compound sheet lobate pahoehoe aquifers.** Unconfined aquifers. Aquifer performance depends on vesicular to massive ratio, percentage of interlobe spaces, and sheet joints in sheet lobes. Low to moderate vertical hydraulic conductivity. Slow recharge where upper part is dominated by hummocky pahoehoe, and moderate where sheet lobe occurs at the top of the aquifer system.

(4) **Simple unconfined aquifer.** Receive spontaneous recharge from rainfall. Groundwater occurs in vesicular and jointed massive basalt subunits. Sheet joints contribute ground water occurrence and movement. Moderate to high vertical hydraulic conductivity. However last word has not been spoken as yet.

**COASTAL AREAS: Hydrodynamic and Hydrochemical Equilibrium**

There is no dearth of water in the coastal areas, but it is beset with high salinity precipitating severe drinking water crises. These are consequence to overexploitation, or from marine deposits of geological past, or even due to dissolved salts concentrated in arid climate of Rajasthan. High arsenic (>0.3mg/L) in groundwater of Lower Bengal Delta, and fluoride (>1.5 mg/L) in groundwater of Rajasthan, Peninsular and other states are two lethal pollutants. Nitrate contamination (>45 mg/L) from nitrogenous fertilisers; and heavy contaminants from sugar cane fields and urban runoff. There is no dearth of water in the coastal areas, but it is beset with high salinity precipitating severe drinking water crises. These are consequence to overexploitation, or from marine deposits of geological past, or even due to dissolved salts concentrated in arid climate of Rajasthan. High arsenic (>0.3mg/L) in groundwater of Lower Bengal Delta, and fluoride (>1.5 mg/L) in groundwater of Rajasthan, Peninsular and other states are two lethal pollutants. Nitrate contamination (>45 mg/L) from nitrogenous fertilisers; and heavy contaminants from sugar cane fields and urban runoff.

**POLLUTION: A Menace**

Groundwater is generally fresh, suitable for all uses but polluted in some areas due to either anthropogenic influences or geogenic causes. High salinity, the largest of pollutants is mainly due to NaCl dissolved from transgressing seawater in the coastal areas, or upconing of saline water consequent to overexploitation, or from marine deposits of geological past, or even due to dissolved salts concentrated in arid climate of Rajasthan. High arsenic (>0.3mg/L) in groundwater of Lower Bengal Delta, and fluoride (>1.5 mg/L) in groundwater of Rajasthan, Peninsular and other states are two lethal pollutants. Nitrate contamination (>45 mg/L) from nitrogenous fertilisers; and heavy contaminants from sugar cane fields and urban runoff.
metal contaminants from municipal and industrial waste waters like Pb, Cr, Cd etc, are also reasons for hazardous groundwater pollution. Recent reports of uranium pollution of groundwater in the northwestern parts of the country pose a new crisis. Thus, pollution is a veritable threat to groundwater sustainability. For preventive and remedial actions studies should be stepped up on locating pollution sources, pollutant load, release mechanism and mobility.

UNSTABLE GROUNDWATER REGIME: Impact of Development

Unbalanced groundwater regime is manifestation of its over-exploitation as its draft exceeds recharge. This is a fast emerging problem. Since groundwater is used by millions, its uncontrolled development leads to desaturation of aquifers; declining water levels; well yields and agricultural production; rising cost of well construction; water lifting and power consumption; degrading groundwater quality; loss of employment; depleting base flows of streams; scarcity of drinking water; consequent migration of people; and farmers in debt trap committing suicides. Out of the total utilizable groundwater recharge of 411.30 BCM in the country the total groundwater draft is 253.06 BCM reaching a stage of 62%. But groundwater is over-exploited in Punjab, Haryana, Rajasthan and NCT Delhi (133-172%), while Tamil Nadu, Gujarat, Uttar Pradesh, Karnataka are in advanced stages of development (64-77%). Further, out of 6584 blocks/taluks in the country, nearly 20% fall under overexploited or critical category.

Figure 5 presents a case study on long-term declining trend of groundwater levels in Karnataka as groundwater draft doubled during 1992-2011. Further, 33% monitoring wells in 1992 showed high nitrate (>45 mg/L) and 9% high fluoride (>1.5 mg/L), the numbers increased to 45% and 17% respectively in 2004. Loss of command area in Karnataka due to drying of tanks and wells has caused a colossal financial cost of 323 crores (Geol. Soc. India Mem. 69, 2008). This has led to social, economic and environmental strains. In no case groundwater draft should exceed its recharge potential.

Effect of Mining on Groundwater Regime

Kolar Gold mining areas in SW Karnataka have recorded long term (1909 to 2004) depletion of pre-monsoon groundwater levels, the deepest being 49.91 m. (Ravindra and Sharma, Geol. Soc. India Mem. 67, 2008, p.543). Dewatering in the mines, about 3000 meters deep, was of the order of 0.3-0.4 MCM of water/km² annually of the...
fractured zone of the mines area, as against annual recharge of 0.09 MCM/Km², thus causing an annual drawdown of roughly 3 m over 4 km² of the area. Further, several major fractures connecting Kolar terrain at higher altitudes with the Palar valley region might have been enhanced or opened up by mining and tunneling operations facilitating gravity drainage of groundwater to lower altitudes of the river valleys. There are many such examples of anthropogenic interference with groundwater regime.

**GLOBAL WARMING AND CLIMATE CHANGE: Impact on Water Resources**

Global warming and climate change may have major impact on water resources. The mean surface temperature may rise by 3°C by 2050 with decrease in winter precipitation (5-25%) and increase in monsoon rainfall (10-15?). Droughts and floods will increase in frequency. In northeastern India, eastern Madhya Pradesh, parts of Gujarat and Kerala precipitation may decline (-6% to -8% of the normal) reducing recharge, while northern Andhra Pradesh and northwestern India may see increase in rainfall (10-12%) enhancing groundwater recharge and benefitting overexploited aquifers. As evapotranspiration increases with rising temperature, crop water and drinking water requirement will be more, and hence demand for groundwater. Further, with the anticipated melting of Himalayan glaciers and drying of rivers by 2050-2075, hydrology of glacial melt fed rivers will undergo remarkable changes impacting groundwater as well. Drinking water availability and crop production will be worst hit. With projected 1 m rise in sea-level, 0.41% of coastal area, and oceanic islands will be lost to sea water inundation along with salinisation of aquifers. Region wise climate change impact has to be assessed and comprehensive mitigation technology decided.

**NEED FOR UNDERSTANDING TOTAL WATER BALANCE**

In a multilayered aquifer system strained condition leads to tricky situations of anomalous rise and fall of groundwater levels as in Mehsana area Gujarat (Fig.6). As revealed by groundwater flow modeling despite adequate lateral flow in deeper aquifer, heavy pumping of deeper aquifers induced leakage from phreatic aquifers through semi-confining layers leaving piezometric levels of deeper aquifers partially recouping and phreatic aquifers declining (Rushton 1986). In a similar situation in the Cauvery delta, Fig.4 illustrates how hydrodynamic and hydrochemical conditions may be in jeopardy. Optimal ecofriendly development of groundwater needs an understanding of the total water balance of the basin or area.

**SUBNORMAL GROUNDWATER DEVELOPMENT**

Groundwater development is subnormal in northeastern states (1-14%) and many other parts of the country. While its low stage of development is an indicator of stunted economic growth, it also impacts environment and ecology adversely. In the canal command water development is an indicator of stunted economic growth, it also impacts 14%) and many other parts of the country. While its low stage of development is an indicator of stunted economic growth, it also impacts environment and ecology adversely. In the canal command water, lake water, groundwater, and recycled grey water is the requirement of smart cities. Integrated management of rain water, river water, lake water, groundwater, and recycled grey water is the foundation of a smart city. In the fast growing metropolis of Bengaluru (Geol. Soc. India Mem., 79, 2011), the primary water supplies from various Cauvery/Arkavathy reservoirs is 1350 MLDs. But transmission or physical losses (UFW) substantially reduce the actual utilization to 810 MLD against a demand of more than 1600 MLD in the city. The deficit is met from 3,26,966 borewells supplying 746 MLD drying up aquifers down to 240 meters depth. Illegal encroachment, garbage dumping, and discharge of untreated sewage have weed out most of the lakes, the traditional source of fresh water and groundwater recharge around the city. Optimal use and augmentation of available water resource through rooftop rain water harvesting, artificial recharge of aquifers combined with watershed treatment in the catchment, groundwater legislation prohibiting further borewell drilling and regulating bore well based water markets, will revive hydrology, ecology and environment of the city’s water bodies and reservoirs, ameliorating water crisis. Further, the substantial quantity of waste waters (800-1000 MLD), if treated and recycled may meet city’s water shortage to a great extent. The huge transmission losses of Cauvery water should also be plugged. Bengaluru presents a comprehensive replicable model of water supply management for fast developing cities facing chronic water shortage.
MANAGEMENT SOLUTIONS: SCIENCE AND TECHNOLOGY

With increasing water demands, groundwater extraction is poised for steep escalation in the coming decades, foreboding a crisis situation, and hence careful ecofriendly management of this vital resource of the country is a necessity. Thus, the guiding principles in addressing these challenges are: (1) exploration and delineation of new aquifers; (2) regulated development without exceeding recharge potentials; (3) protection from pollution and remediation of contaminated groundwater; (4) conservation and augmentation of this finite resource; (5) public participation in groundwater development and management. Science and Technology has a big role in groundwater management.

**Selection of new aquifers:** Large tracts of the arid-semiarid hard rock terrain and hilly upland areas still remain unexplored resulting in meagre development of groundwater. Exploration should be stepped up adopting a multi-disciplinary approach including remote sensing, geophysics (electrical & electromagnetic probes) and modeling aiding delineation of unknown aquifers, assessing their potentials, and quality. Hydrogeological mapping should include structural mapping in tectonically disturbed hard rock terrains. Scanning of satellite imageries helps in delineating hydrogeomorphic units, recharge-discharge areas, fracture lineaments favorable for groundwater storage. Heliborne TMT survey is another useful geophysical tool in subsurface imaging of the formations/structures holding possible groundwater storages based on variations in physical properties of the formations supported by ground-based hydrogeological data (Fig. 7) (Subhaschandra et al., 2016, Geol. Soc. India. Spec. Publ. no.5).

**Groundwater Modeling:** Modeling studies, both mathematical and stochastic, allow in-depth understanding of the flow dynamics in fractured hard rock and alluvial aquifers, between weathered saturated zone and fractured media, as also between unsaturated and saturated zones. It also helps in creating alternate scenarios for optimal resource development. With S&T playing a big role in groundwater exploration and management, modeling is taking the center stage.

**Regional Aquifer Mapping:** The logical output of multi-disciplinary studies is the ongoing Regional Aquifer Mapping for preparation of Master Plan for groundwater development at microlevel, and to start with in the overexploited areas.

**Disciplined use of resource:** Estimation, conservation and augmentation.

(a) **Estimation:** Precise estimation of resources is basic to optimal development and management of resource. Groundwater draft should not exceed its recharge potential. GEC 97 currently in use for estimation of resource, depends upon specific yield, water table fluctuation, and several other recharge norms which need to be refined through intensive field studies at microlevel in view of lithological heterogeneities and tentative nature of the values used. Soil moisture balance, tracer techniques are two advanced computational methods which may be used more and more.

(b) **Groundwater Monitoring:** Groundwater monitoring which is carried out through nearly 70,000 wells in the country, and provides water table fluctuation data and water level trend, should be strengthened, data digitized and made accessible to the stake holders and users for awareness of groundwater management.

(c) **Water conservation & augmentation:** Conjunctive use of surface water and groundwater is the most efficient method of water conservation, and promotes optimal use of all water resources, equitable water allocation in canal commands, and rectification of rampant water logging in the irrigation commands, enhancing agricultural output and productivity. CGWB’s pilot projects in IGNP in Rajasthan, Hirakud command in Odisha, Koshi command in Bihar, Sarda Sahayak command in Uttar Pradesh, Nagarjun Sagar in Telangana have brought to light replicable conjunctive use models.

Rainwater harvesting and artificial recharge are two modern innovations for groundwater augmentation: saturating overexploited aquifers, harvesting and conserving surplus monsoon runoff in the subsurface formations for usage at times of need. These are traditional, simple and cost effective techniques including terracing, contour bunding, gully plugging, percolation tanks, check dams, subsurface dams which can be successfully implemented as part of integrated watershed management through community participation (JGSI, vol 85, 2015, pp386-389) as in Arwari watershed in Rajasthan, Ichalahalla watershed in Karnataka or Jain watershed in Western Maharashtra which turned around the economy in the shortest possible time.

(d) **Prevention of pollution:** Mapping of vulnerable zones through use of DRASTIC technique or solute transport modeling are fundamental to preventive actions and pollution attenuation. Failing such pre-emptive actions this strategic resource will be rendered useless. Rainwater harvesting and artificial recharge is a cost effective process of diluting pollution in groundwater. Using alternative sources of water or its physico-chemical treatment are the other methods commonly resorted to. Research and development of people friendly and cost effective methods are in utmost need.

Summing up, in the wake of anticipated water scarcity in near future, as all known sources of utilisable waters may be exhausted by 2050, in depth knowledge of groundwater domain is a must for its sustainable use and management. Groundwater is a common pool resource used by millions. The community should be apprised of the perils of its overdraft, pollution, or uncontrolled development activities, and of the conservation practices. Community participation in groundwater management constitutes a core element of our National Policy: "Know your aquifer and manage your aquifer"."