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Review Article

Recent Hydrogeological Research in India

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The hydrogeological setup of India represents a wide variation, from rugged Himalayan mountainous region in the north, extensive Indo-Ganga-Brahmaputra floodplain and deltaic region in the central and eastern part, aeolian- alluvial deposits in the west, vast basalt flows in the west central part, gently undulating central and southern region underlain by Precambrian crystalline, sedimentary and metamorphic, coastal deposits along the east coast etc.

The research on hydrogeology has got special socioeconomic significance because India is now the largest extractor of groundwater in the world. The impact of overexploitation of the resource is surfacing in large parts of the country, in the form of lowering of water level, dwindling yield of well and deterioration in water quality.

In recent years, extensive studies have been carried out in this field of geoscience. We have discussed these in different segments, after enumerating the broad hydrological framework of India. The segments are 1. Hydrogeological investigations in Indo-Ganga-Brahmaputra Plains holding one of the potential aquifer systems 2. Groundwater chemistry and contamination issues in Peninsular India 3. Urban hydrogeology 4. Groundwater modeling 5. Ground water exploration 6. Groundwater recharge and associated quality issues 7. Remote sensing and GIS applications 8. Coastal aquifers and 9. Groundwater management.

It is observed that the potential groundwater reserve in the Indo-Gangetic basin and the Peninsular part of India has two serious issues: 1. Overexploitation of groundwater mainly in the western and north western parts and also in southern peninsular India in pockets and 2. Groundwater quality deterioration by anomalous concentration of arsenic, fluoride and salinity. The findings of the research will help in understanding the hydrogeological complexities in its entire gamut and also offers insight into the ways for sustainable management of groundwater resource of the country.

Keywords: **India, Hydrogeology; Groundwater Extraction; Indo-Gangetic Plain; Groundwater Quality; Fluoride; Arsenic; Groundwater Pollution; Groundwater Modeling**

Introduction

India, spanning over approximately 3.2 million km^2, exhibits wide variety of rock types, ranging from Recent deposits along the flood plain of river, air borne sediments in arid areas and the extensive coastal deposits, to some of the oldest igneous and metamorphic suite of rocks of the world. In accordance with the wide range of rock types, there is wide variation in hydrogeological settings, groundwater occurrence, flow regime and a wide variety of rock-water interaction in the country.

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Aquifer Systems in India

The country is broadly divided into different segments depicting different hydrogeological framework. Central Ground Water Board (CGWB, 2014) has identified fourteen principal aquifers systems in India (Fig. 1). A brief description of the principal aquifer systems is given below.

Alluvial Aquifers

The Quaternary sediments comprising Recent Alluvium, Older Alluvium, Aeolian and coastal deposits

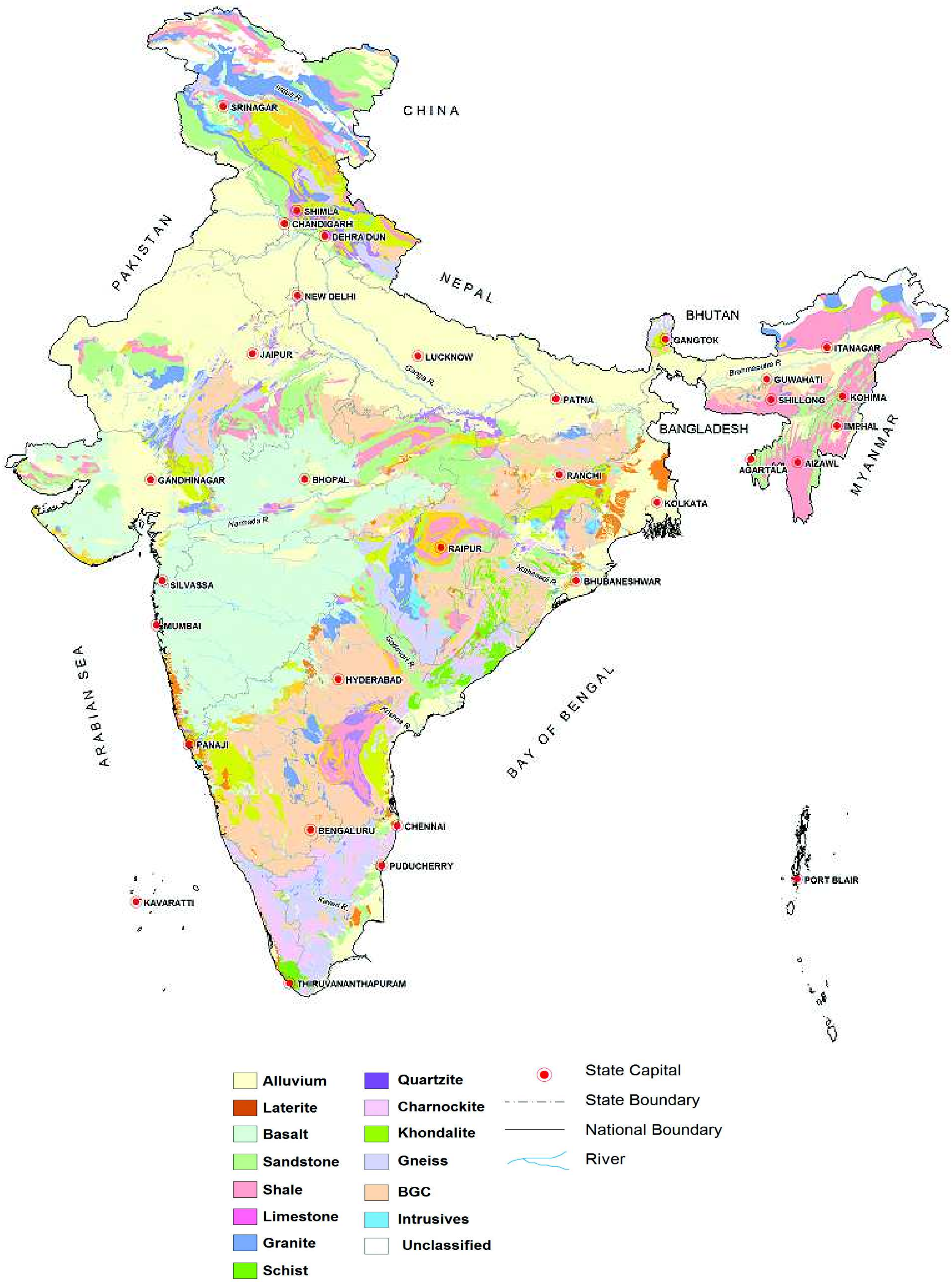

Fig. 1: Principal aquifer systems of India (adopted from CGWB 2014)

are clubbed into this group. The sediments are essentially composed of clay, silt, sand, pebble and kankar and hold potential groundwater reservoirs for extensive development. The Indo-Ganga-Brahmaputra Plains represent a thick unconsolidated aquifer system, holds enormous groundwater reserve. In many parts, these aquifer systems are bestowed with high incidence of rainfall; thus get significant annual recharge rendering them excellent source for drinking and irrigation. In addition to the annual recharge from rainfall, there exists a huge groundwater reserve in the deeper passive recharge zone as well as in the deeper confined aquifers which extend even beyond 600m below ground level (bgl) or so, which has largely remained unexplored. The unconsolidated aquifers along the coast are equally productive but show wide variation in the water quality, both spatially and vertically, thus imposing quality constraint for groundwater development. The groundwater prospect of the Aeolian deposits is constrained by deep water level, over exploitation and salinity hazard.

Laterite

Laterites are formed by the leaching such as chemical weathering of wide spectrum of rocks, ranging from sedimentary, metamorphic and crystalline types. Laterites are extensively developed aquifers in the Indian peninsular states. They form potential aquifers along valleys and topographic lows where the thickness of the saturated zone is more and can support large diameter open wells and much beneficial for domestic and irrigation purposes.

Sandstone and Shale

The aquifers belong to this group range in age from Carboniferous to Mio-Pliocene. The Gondwana System and the Tertiary deposits along east coast, like Cuddalore sandstone, in western part of India like Lathis as well as in the north-east like Tipam and their equivalents are most productive aquifers.

Carbonate Rocks

The consolidated carbonate rocks such as limestone, dolomite and marble fall in this group. Among those limestone is the most predominant and productive from groundwater prospect view. The fractured zone and solution cavities constitute the most potential aquifer zones.

Basalt Flows

The Deccan Traps made up of stratified basalt flows, covers about 1.5 million km^2 areas, spread largely over the states of Maharashtra and also in parts of Madhya Pradesh, Gujarat and Karnataka. Besides, small patches of basalt flows are also observed in other state like in Jharkhand.

Groundwater occurrence and movement in basalt flows is controlled by nature, thickness and extent of weathering, presence of vesicular zones in individual flows, the fractures as well as the nature of intertrappen layers. These aquifers generally have medium to low permeability. Contrasting water bearing properties of lower massive and upper vesicular parts in a flow unit sometime result in multiple aquifer system as number of flows are stacked in an area.

Crystalline Hard Rock Aquifers

Granite, gneisse and the suite of metamorphic rocks including khondalites and charnockites as well as consolidated Precambrian sedimentaries such as Vindhyan and its equivalents fall under this category. Weathered zone and the underline fracture system form good aquifers. The fracture system in these aquifers includes fractures; joints, bedding planes etc. and they are encountered even beyond 400 mbgl. The fractures when densely zoned and interconnected forms potential aquifer. But generally the fractures are anisotropically distributed and targeting groundwater poses a challenge. The weathered zone thickness generally varies from 10 to 30 m and holds some groundwater potential and developed through dug wells.

Research in Hydrogeology

Significant works are going on in this domain on wide ranging subjects, from aquifer characterization, targeting potential aquifer, rock-water interaction, groundwater contamination, recharging aquifers and use of state of the art tools. The researches carried out in the last five-six years have been captured and grouped in nine categories as below.

Hydrogeological Investigations in Indo-Ganga-Brahamputra Plains

Indo-Gangetic Plains in India is experiencing one of the most intensive groundwater extractions in the world; mainly because of spiral rise in the demand from the irrigation sector (Mukherjee *et al*., 2015a). The sediment in the basin was deposited by past and present day rivers from the Himalaya and cratonic provinces (Sinha *et al*., 2009; Singh, 1996). The Plains form large aquifer system and at places the aquifers are trans boundary in nature, between the states, India-Nepal, India-Pakistan and India-Bangladesh. Efforts have been made to correlate the aquifer geometry and their disposition in relation to geomorphology and neotectonic activity (Sahu and Saha, 2014a; Sahu *et al*., 2010). The younger alluvium in the flood plain of the present day rivers has high groundwater potential (Shekhar *et al*., 2015; Shekhar and Prasad, 2009). The rainfall in the basin varies from less than 25 mm per annum in southern Pakistan to greater than 2000 mm in the Bengal basin (MacDonald *et al*., 2015).

The depth of groundwater level shows wide spatial variation in the Plains. In Brahmaputra plains as well as in West Bengal, Bihar, eastern and central parts of Uttar Pradesh, the water level by and large remains within 20 m below ground. But in the western part like in Haryana, Punjab and Rajasthan, the water levels recede even beyond 60 mbgl. Punjab and Haryana states also experience highest rate of groundwater abstraction in the world (Van Dijk *et al*., 2016)

The total groundwater abstraction from the Indo Gangetic basin is about 205 m^3, which amounts to 20-25 % of total global groundwater abstraction (MacDonald *et al*., 2015). In recent years the groundwater level decline linked to over-exploitation, have been mostly noticed in aquifers of Indo-Gangetic Plains, occupying north-western states of India like Punjab, Haryana, Rajasthan and Delhi (Sarkar *et al*., 2016; MacDonald *et al*., 2015; Dasgupta *et al*., 2014; Saha *et al*., 2010; Tiwari *et al*., 2009; Rodell *et al*., 2009; Chatterjee *et al*., 2009). More than 80 % of the groundwater abstraction is for agriculture. However, localized high abstraction is also observed in urban areas leading to continuous decline of water level. Saha *et al*. (2013) and Dwivedi and Singh (2015) studied the aquifer system and groundwater extraction in Patna urban area, located in the Middle Gangetic Plains. Sinha *et al*. (2013) investigated paleo-channels, which often contain potential aquifers, through resistivity survey. Bawa *et al*. (2014) established that excessive groundwater withdrawal in middle reaches of Yamuna basin has affected river flow.

Groundwater quality issues of the Indo-Ganga-Brahmaputra Plains as well as the entire basin area have been investigated in detail. In the Indo-Gangetic Plains, groundwater quality shows wide spatial variation (Sarkar and Shekhar, 2015; Sarkar and Shekhar, 2013). Arsenic contamination (Saha and Sahu, 2016; Kumar *et al*., 2016; Jangle *et al*., 2016; Chakraborti *et al*., 2016; Alam *et al*., 2016; Shah, 2015; Mukherjee *et al*., 2015a; Singh *et al*., 2014; Sahu and Saha, 2014b; Saha and Shukla, 2013; Shah, 2013; Singh *et al*., 2013a; Raju, 2012a, 2012b; Mukherjee *et al*., 2012a; Dubey *et al*., 2012; Saha *et al*., 2011; Mukherjee *et al*., 2011e; Kumar *et al*., 2010; Shah, 2010; Saha, 2009; Saha *et al*., 2009) and elevated concentration of fluoride (Ali *et al*., 2016; Sarkar and Shekhar, 2015; Shekhar and Sarkar, 2013; Raju *et al*., 2009; Saxena and Ahmed, 2003) in groundwater along with salinity has been identified as the major quality issue (Shekhar *et al*., 2015).

The Indo-Ganga-Brahamputra Plains has attracted the attention of researchers for arsenic contamination of groundwater (Banerjee *et al*., 2012) as evident from large number of research works mentioned above. Though, it was reported about three decades before in West Bengal (Garai *et al*. 1984) from the upstream of Garo-Rajmahal Gap, the initial report was made in 2003 (Chakraborti *et al*., 2003). These findings kick; started researches and various departmental investigations in Middle and Upper Ganga Plains as well as in the Brahmaputra valley.

Saha (2009) had compiled an overview of extent of arsenic contamination, its geographical distribution in the state of Bihar. The mobilization process of arsenic and hydrogeochemical evolution of groundwater has been studied in details in different contaminated pockets (Saha *et al*., 2009; Chauhan *et al*., 2009; Mukherjee *et al*., 2015a; Shah 2015; Kumar *et al*., 2010; Mukherjee *et al*., 2011e; Raju, 2012a). The arsenic contaminated areas are confined along the Holocene deposits and reported both from the Younger and Older Flood Plain, while the Pleistocene deposits are found to be free from contamination (Sahu and Saha, 2014b; Pandey *et al*., 2015). Raju (2012a) studied the hydrogeochemistry of groundwater in Pleistocene deposits. The contaminants areas are underlain by multi aquifer system made up of

Quaternary deposits. Investigation revealed arsenic-free deeper aquifer and their hydraulic separation from the shallow contaminated aquifers (Saha and Shukla, 2013; Saha *et al*., 2010). At places in West Bengal, elevated concentration of arsenic is reported from deeper aquifer (Mukherjee *et al*., 2011e). Saha *et al*. (2013) applied isotopic techniques to understand the recharge mechanism and established that shallow contaminated aquifers get quick recharge from rainfall while the deeper aquifers represent older water having recharge area far off. Researchers also attempted vulnerability analyses and entry of arsenic in the food chain in parts of Middle Ganga Plain and its health impact (Singh and Ghosh, 2011; Singh *et al*., 2011). The fixation of arsenic in the cereal grown in the contaminated region focusing on Bengal delta plain have been discussed in details by Chatterjee *et al*. (2010), Halder *et al*. (2012) and Bhattacharya *et al*. (2010a and 2010b). They conclude that the consumption of groundwater and rice grown using contaminated water are the major pathways of arsenic in human bodies. Sankar *et al*. (2014) had studied geogenic arsenic and manganese contamination in four blocks on either side of the river Bhagirathi in Murshidabad district. Singh *et al.* (2013b) studied heavy metal concentration in groundwater of Satluj basin. Bhattacharya *et al*. (2010a) had studied in detail the arsenic concentration of different rice and vegetables varieties grown in the contaminated areas of West Bengal.

Interesting researches also carried out in various parts of north-east India viz., Barak valley, Brahmaputra Plains, Manipur state and north of Mizoram state on arsenic contamination (Chakraborty *et al*., 2008; Chetia *et al*., 2011; Buragohain *et al*., 2010; Oinam *et al*., 2012; Shah 2012; Kumar *et al*., 2013). In a significant work, Mahanta *et al*. (2015) studied arsenic enriched groundwater regime within Brahmaputra flood plains. These authors observed the origin, distribution and processes of arsenic release by investigating the groundwater chemistry and subsurface sedimentological characteristics.

Beside arsenic, fluoride and salinity contamination in the groundwater system is predominantly observed in arid and semiarid regions confined to western and north western parts (Singh and Mukherjee, 2014). Sporadic fluoride contamination has also been observed in eastern part of the Ganga basin. The deltaic area of West Bengal and Bangladesh also has aquifers bearing saline groundwater.

Ali *et al*. (2016) observed that high values of fluoride in groundwater are mainly confined to arid and semi-arid zones in the world as well as in India. Hussain *et al*. (2013) studied fluoride contamination in groundwater of 121 localities in Bhilwara district of Rajasthan. The groundwater from deep aquifers shows fluoride concentration in the range of 0.5 to 5.8 mg/L. Based on the concentration of fluoride, these authors categorized the district into five categories.

Raju *et al*. (2012) studied fluoride hazard and assessment of groundwater quality in the semi-arid Upper Panda River basin, Sonbhadra district, Uttar Pradesh. Further, Raju (2016) studied the details about the genesis of fluoride in Padwakodari area of the same district. Singh *et al*. (2011) and Mukherjee *et al.* (2011d) studied groundwater quality of Pokhran area, Rajasthan. The process of fluoride enrichment in Thar desert was studied by Singh *et al.* (2012)

Sarkar and Shekhar (2015) studied hydrochemical facies and major ion variations in South West district of Delhi. They attributed this to geology as main geogenic source while heavy groundwater abstraction to be major anthropogenic source. Shekhar and Sarkar (2013) studied groundwater quality in the vicinity of Najafgarh drain in Delhi NCT. It was inferred from this study that anthropogenic contamination has much impact on the water quality in the vicinity of Najafgarh drain. The impact of landuse on groundwater quality has been also studied by Mukherjee *et al.* (2011b) and Srivastava *et al.* (2014)

In Uttar Pradesh, Singh *et al.* (2015) studied hydrochemistry of groundwater in parts of Chandauli-Varanasi region where the domination of cations and anions was observed in the order of Na > Ca > Mg > K and HCO_3 > Cl > SO_4 > NO_3 > F. Alam and Umar (2013) in an exhaustive research discussed about the origin and distribution of trace element in Hindon Yamuna region in Upper Ganga Plain. The study reveals anthropogenic sources for the contamination. Further, Khan *et al*. (2010) studied trace elements in groundwater of western Uttar Pradesh. These authors observed high concentration of Fe, Mn, Sr, Cr, Al and Pb above than the permissible limit in the groundwater. These authors attributed this high value to the industrial effluents of sugar mills, pulp and paper factories and municipal waste in the area.

Raju *et al.* (2011) studied hydrogeochemical parameters for groundwater samples of the Varanasi, Uttar Pradesh. These authors observed high concentration of nitrate in about 18% of the groundwater samples and attributed this to local domestic sewage, leakage from septic tanks etc. In addition, high nitrate concentration has also been reported from other parts of the Gangetic Plains and attributed to the heavy dose of fertilizers used for agriculture. However, it has been observed that the deeper aquifers are less vulnerable from nitrate contamination (Saha and Alam, 2014).

Oinam *et al.* (2012) studied Imphal and Thoubal district of Manipur and observed that groundwater is predominanetly Ca–HCO_3 type and mixed Ca–Na–HCO_3, Ca–Mg–Cl type facies. Few samples also demonstrate Na–Cl and Ca–Cl type facies.

Shah and Umar (2015) used stable isotope content and deuterium excess in groundwater in parts of Unnao district in Uttar Pradesh, which indicates the single source of recharge in both pre and post-monsoon seasons. Investigation of the salinization of aquifers in Delhi has been attributed to various reasons by Kumar *et al.* (2015). Mukherjee (2015) discussed about impact of climate change on water quality variation.

Geology is the primary control on groundwater quality variation linked to geogenic sources (Sarkar and Shekhar, 2015; Shekhar and Sarkar, 2013; Sarkar and Shekhar, 2013), however, anthropogenic forcing has also left its distinct mark on groundwater quality in the basin.

Groundwater Chemistry and Contamination Issues of Peninsular India

Significant researches have been done on hydrogeochemical evaluation of groundwater emphasing on the mobilization and distribution of various contaminants such as fluoride, uranium and nitrate. In a study, Manikandan *et al.* (2014) investigated Krishnagiri district of Tamil Nadu and found that higher values of fluoride were associated with Mg-Na-HCO_3 type facies. Further, they linked this to weathering of Mg bearing minerals such as biotite, hornblende and weathering of apatite/hydroxyapaptites from the charnockites found in the region. The genesis and distribution of fluoride in Nalgonda district, Telangana state was discussed by Brindha *et al.* (2010). Besides fluoride, the nitrate is another issue of groundwater quality in the peninsular India. In same areas, Brindha *et al.* (2010) have discussed the nitrate pollution and related its origin to poor sanitation facility and indiscriminate dumping of municipal waste. Dar *et al.* (2011) observed fluoride concentration in the range from 1 to 3.24 mg/L in parts of Palar river basin in Kancheepuram district of Tamil Nadu. Further, Total Dissolved Solids in the area was found to be in the range from 70 to 467 mg/L. Mukherjee *et al.* (2011c) use statistical approach to characterized groundwater chemistry. Srinivasamoorthy *et al.* (2010) studied Mettur region of Tamil Nadu and observed fluoride concentration in groundwater in the range from 0.1 to 2.8 and 0.4 to 4 mg/L in pre- and post-monsoon seasons. The anion and cation were observed to be in the order of Cl> HCO_3> SO_4> NO_3> PO_4 and Na> Ca> Mg> K.

Several authors have studied the hydrogeochemistry of groundwater and vulnerability of the aquifer to pollution in hard rock aquifer of the peninsular India. Rina *et al.* (2011), Singh *et al.* (2012a and 2012b) studied hydrogeochemical evolution of groundwater. Avtar *et al.* (2012) used statistical approach to understand groundwater chemistry of Bundelkhand region. Patel *et al.* (2016) used multivariant statistical analyses to assess the groundwater quality of the Swarnamukhi river basin, Andhra Pradesh. Prasanna *et al.* (2011), Senthilkumar and Elango, (2013), Rajesh *et al.* (2015), Brindha and Kavitha (2014), Brindha *et al.* (2013), Kumar *et al.* (2014) and Sonkamble *et al.* (2012) investigated aquifers in various rock domains like granite, gneiss, schist and basalt to enumerate the geochemical evolution of groundwater and its suitability for various use.

Keesari *et al.* (2014) studied the geochemistry of groundwater using isotopic composition in arid region of western India. The area is affected by salinity whose origin has been found to be leaching of marine sediments besides contribution of evaporates from soil zone. The spatial temporal variation of bromide in the hard rock aquifers in groundwater has been studied by Brindha and Elango (2013). They opined that the sources of bromide are granitic rocks and fertilizers.

In a significant study, Thivya *et al*. (2016) evaluated uranium concentration in groundwater, the effect of lithology on hydrochemistry and factors controlling its distribution in granitic aquifers of Madhrai district, Tamil Nadu. Results indicate that the highest uranium concentration i.e. 113 µg/L was found in granitic terrains of this region and about 10% of the water samples exceed the permissible limit for drinking water.

Mondal and Singh (2011a and 2011b) dealt with the chemical analysis of groundwater affected due to untreated effluents from 80 functioning tanneries forming a tannery belt in Southern India. It was found that the quality of groundwater around the tannery cluster deteriorated mainly due to the extensive use of salts.

Urban Hydrogeology

The rapid urbanization and exponential increase in extraction of groundwater in urban areas have necessitated studies on urban hydrogeology in cities like Bangaluru (Majumdar, 2012), Chennai (Raju *et al*., 2013b), Varanasi (Raju *et al*., 2011) and Delhi (Chatterjee *et al*., 2009; Sarkar *et al*., 2016). Most of the urban centres have tendency to overexploit groundwater resources. The groundwater management options suggested for the urban centres mostly includes identification of vulnerable areas and measure to mitigate stress on the groundwater system (Raju *et al*., 2011; Shekhar *et al*., 2015).

Groundwater Modeling

Groundwater modeling is widely used as a tool for applied hydrogeological study. It is often used in assessment of the impact of possible anthropogenic influences on groundwater system. Senthilkumar and Elango (2011) used groundwater modeling to assess the utility of subsurface barrier for augmenting groundwater reserve and to minimize sea discharge of groundwater. Rao *et al*. (2014) used numerical modeling study for assessing long-term water resources availability in the Godavari basin of India. Shekhar and Rao (2010) discusses about the issues related to groundwater modeling in Palla well field of Delhi. Brindha and Elango (2015) used DRASTIC and models derived from it to map vulnerable zones for pollution in weathered rock aquifers of southern India.

Groundwater Exploration

Groundwater exploration in India is being carried out mainly by Central Ground Water Board (CGWB). The data is compiled in to thematic maps for use by different agencies and academic institutions. Further the scientific input in to groundwater exploration has been provided by individual researchers. Madhnure (2014) identified weathered aquifers in basaltic and granitic terrain of Nanded District, Maharashatra. They locate the productive zones in the fractured basalt and estimated the aquifer parameters. Similarly, in Kolar district of Karnataka, Hegde *et al*. (2012) identified the potential aquifers and estimated the aquifer parameters. Shekhar *et al*. (2009) presented the average value of aquifer parameters for different aquifer system of Delhi using exploration database of CGWB. Mondal and Das (2012) used step drawdown test for recommending safe yield for drinking water supply in Salur Mandal, Vizainagaram in Andhra Pradesh.

Groundwater Recharge and Associated Quality Issues

The scientific study on groundwater recharge has gained importance of late. This is primarily because of overexploitation of groundwater resources in many parts of India. Kaliraj *et al*. (2013) proposed suitable artificial groundwater recharge sites along Vaigai upper basin in the Theni district, Tamil Nadu, India. Raju *et al*. (2013a) designed subsurface dams and studied the impact of dams on water quality and seawater intrusion into the coastal aquifers in the Kalangi River basin, Nellore district, Andhra Pradesh. Renganayaki and Elango (2013) carried out a study to understand the impact of water stored in a check dam on groundwater quality near Chennai, Tamil Nadu. Mondal *et al*. (2012b) assessed natural groundwater recharge in unconfined aquifers in hard rock aquifers in southern India using entropy-based approach. Selvam *et al*. (2015) adopted an integrated approach to delineate groundwater recharge potential zones using remote sensing and GIS techniques in Kovilpatti Municipality, Tamil Nadu. Kaliraj *et al*. (2015) identified groundwater recharge potential zone and suitable sites for artificial recharge structures in the Vaigai basin, Theni district; Tamil Nadu using GIS-based multi-parameter weighted overlay method. Kaliraj *et al*. (2013) studied the groundwater recharge potential zones along Vaigai upper basin in the Theni district, Tamil Nadu. Samadder *et al*. (2011) emphasized on paleochannels and their potential for artificial groundwater recharge in the western Ganga plains. Soni *et al*. (2014) suggested optimal environmental flow of 50 percent in river Yamuna for it to carry out its function of recharging the flood plain aquifer.

Remote Sensing and GIS Application

Application of remotely sensed data is widely used for groundwater mapping and targeting groundwater. Anbazhagan and Jothibasu (2014) carried out sustainable groundwater potential mapping through geoinformatics in the Uppar Odai sub-basin in Amravati River basin, southern India. The geomorphology and lineaments were interpreted from IRS P6 LISS III satellite data. This was further integrated with resistivity data for generation of groundwater potential map. Chowdhary *et al*. (2009) had applied remote sensing and GIS based study and assessed groundwater potential of the coastal in West Medinipur district of West Bengal.

Magesh *et al*. (2012) integrated the remote sensing data on geographical information system platform for the exploration of groundwater in Theni district, Tamil Nadu. Deepika *et al*. (2013) identified the groundwater potential zones of Gangolli baisn of Karnataka using GIS. Similarly with the help of remote sensing and GIS, Avinash *et al*. (2011) mapped geomorphic features of Gurpur river basin of Karnataka, India. Varade *et al*. (2012) used remote sensing and GIS technique to identify potential sites for water conservation measures like gully plugs, earthen check dams, continuous contour trenches, percolation tanks, cement bandhara, aforestation and farm ponds in Nagpur district of Maharashtra. Groundwater potentiality has been studied by adopting remote sensing and GIS technique in hard rock aquifers in West Bengal by Jha *et al.* (2012) and in the arid region of western India by Mukherjee *et al.* (2012b).

In addition to remote sensing, various maps and existing data were placed in GIS platform to work out the data gap on various investigations in terms of mapping of aquifers and groundwater potentiality in parts of Karnataka state underlain by hard rock aquifers (Vittala *et al*., 2013) and in Punjab by Mukherjee *et al.* (2011b). Water level situation and other layers was field data. Remote sensing in a GIS platform was tried in alluvial areas successfully by Ganapman *et al*. (2009) and Saha *et al.* (2006). The overlay analyses had also tried to prepare vulnerability map of the coastal aquifers (Sathis and Elango 2011). Gopinath *et al*. (2014) had applied geospatial technology in drought monitored by NDVI mainly using Terra satellite products in southern parts of India. Rajaveni *et al*. (2015) researched on delineating groundwater perspective zones in Nalgonda district of Telangana state. Mukherjee and Veer (2014) has applied artificial neural network and image processing for development of water resource management plan in parts of Hindon basin. Further, Mukherjee *et al.* (2015b) discussed about application of geospatial and geostatistical techniques for groundwater potential zone delineation.

Coastal Aquifers

The costal aquifers are important as they are sustaining huge demand from drinking and irrigation. On account of heavy abstraction the coastal areas have also become priority research sites. Rina *et al.* (2011 and 2013) studied hydrogeochemistry of Sabarmati basin including its coastal aquifers. Selvam *et al*. (2013) assessed the groundwater quality around Tuticorin Corporation limits, Tamilnadu *vis-a-vis* utility of water for different purposes. Sivasubramanian *et al*. (2013) identified the chemical processes that control hydrochemistry in Kadaladi block of Ramanathapuram District, Tamilnadu. Prasanth *et al*. (2012) carried out a hydro-geochemical study in Alappuzha district of Kerala to assess suitability of water for different uses. Mondal *et al*. (2012a) used geophysical survey in industrial belt of Southern India for estimation of salinity variation. Chandrasekar *et al*. (2013) identified seawater intrusion in the aquifers of southern Tamil Nadu. Prasanth *et al*. (2012) examined the suitability of ground water quality for irrigation and domestic purpose in of Alappuzha District, Kerala. Sathish and Elango (2011) identified groundwater quality variation and proposed vulnerability map of the south Chennai coastal aquifer, while Sankaran *et al*. (2012) identified groundwater pollution and saline intrusion through Uppanar River, which flows parallel to sea coast in Cuddalore. Singh and Jha (2014) researched on tide dynamics in the coastal aquifer system. In another significant work, Jha and Singh (2014) applied genetic algorithm techniques to model tide-aquifer interaction. Reddy and Gunaseker (2013) studied the groundwater quality in coastal areas of Andhra Pradesh and its impact on human health particularly the kidney.

Groundwater Management

Sarkar *et al*. (2016) use DPSIR (Drivers, Pressures, State, Impacts, and Responses) approach and successfully evaluated the groundwater environment of Delhi. Further, Shekhar *et al*. (2015) explained various ways of groundwater management in North district of NCT Delhi. The authors divided the district into three distinct hydrogeological domains based on the occurrence and availability of groundwater similarity. Groundwater potential in these domains were worked out.

Madhnure *et al*. (2015) has carried out an integrated study to assess groundwater development possibility in semi-arid Madhram watershed in Telangana. Higher transmissibility, specific yield and infiltration rate were observed in the recharge area and those decrease gradually towards the discharge area. Analyses and mapping of water levels are essential inputs for groundwater management. In a significant work, Mondal and Singh (2012) applied entropy based approach to assess the groundwater monitoring networks stations and water levels maps those are prepared based on existing monitoring stations. Rajaveni *et al*. (2014) explained how to assess the water levels in relation to dykes, drainage, lineament and weathered zone thickness. The utility of geophysical investigation to understood the hydrogeological complexities in granitic terrains in Telangana state has been described by Sonkamble *et al*. (2014). In an interesting study, Yogeswar *et al*. (2012) investigated the impact of sewage irrigation and groundwater contamination around Roorkee region in upper Ganga plain using advanced geophysical technique like direct current resistivity and radio magnetotelluric methods.

Conclusions

It is observed that the diverse hydrogeological setup of India and the varied forcing on groundwater system has resulted in hydrogeological domain specific issues. This requires remedial measures specific to the hydrogeological domains. It is concluded that the Indo-Gangetic Plains has twin problem of groundwater overexploitation in western part and its quality deterioration at places. The arsenic contamination of groundwater is mainly noticed in eastern part of the Gangatic Plains in states like West Bengal, Bihar and Uttar Pradesh. While fluoride contamination in groundwater is mainly restricted to arid and semi-arid regions of the basin. Hardrock areas also show overexploitation of the groundwater resources in certain pockets. Further, fluoride contamination in groundwater has been generally observed in hard rock region of southern India. The inland salinity in western India and coastal aquifer salinity needs to be prudently managed to prevent further water quality deterioration. This becomes important as the vulnerability of coastal aquifers to sea water intrusion and problem of inland salinity upconing are becoming major issues. Remote sensing and various geophysical and isotopic technique have proved to be successful tools for groundwater exploration mainly in hardrock areas of the country. The efficacy of numerical modeling for groundwater resource management has been established in different hydrogeologic environment in India.

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