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Recent Scientific Perspectives on the Indian Hydrogeology

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The hydrogeology of India represents one of the diverse systems in the world. The hydrologically distinct Himalayan highlands and its foreland basins with deposits of indo-Ganga Brahmaputra system gradually merges with the cratonic provinces of central and south India, fluvioaeolian deposits of west and the basaltic province of the Deccan plateau. The tremendous socio economic significance of groundwater in India can be appreciated by the fact that about 62 % of water used in irrigation, about 85 percent of rural water supply and more than 50 % of urban water consumption is extracted from aquifers.

The acute over-exploitation of groundwater resources in some parts of India, deterioration in groundwater quality both from geogenic and anthropogenic sources, declining well yield, the quest for sustainable use of groundwater resource and the need to map and understand the aquifer system have acted as stimulus for researchers throughout India. The paper deals with a brief introduction of Indian hydrogeology and reviewed the huge volume of researches carried out in the recent past under nine sub themes representing the rainbow of groundwater research in India.

Keywords: **India; Hydrogeology; Groundwater; Water Quality; Groundwater Modeling; Environmental Isotopes; Aquifer Mapping; Hydrogeological Processes; Well Hydraulics; Coastal Hydrogeology**

Introduction

India is a composite mosaic of united cultural, religious and culinary diversity and so is the hydrogeology of the country. With the areal extent of about 3.2 million km^2, the Indian hydrogeology encompasses groundwater system of the vast Indo-Ganga-Brahmaputra alluvial Plains and delta fronts of the major rivers debouching in the Bay of Bengal, young folded mountain system of Himalaya; varied rock types of the peninsular cartons, basaltic Deccan Traps, semi-consolidated Tertiary and Mesozoic deposits and the coastal aquifer systems (Saha *et al*. 2016). The principal aquifer systems of India are best shown as Fig. 1.

On the basis of similarity in the mode of occurrence of groundwater, initially Taylor in1959, divided India into eight groundwater provinces which was well presented by Karanth (1987). Recently Saha *et al*. (2016) for the first time presented the recent classification of Indian aquifers from CGWB (2012) where the aquifers of India are classified into 14 principal aquifer systems (Fig. 1).

A recent article by Saha and Ray (2019) highlighted that the considerable population of India experiences water scarcity and the per capita water availability of India is likely to reduce to 1140 m^3 in 2050. They opined that the aquifers of India provides about 62% of water used in irrigation, in which about 85% is the rural domestic consumption and 50% of the urban consumption. The total estimated annual effective recharge into the phreatic aquifers in the country is 398×10^9 m^3 of which 70% is from rainfall and the rest is from other sources (CGWB 2014; Saha and Ray 2019). The exploitation of groundwater resources is often reflected by the secular decline in

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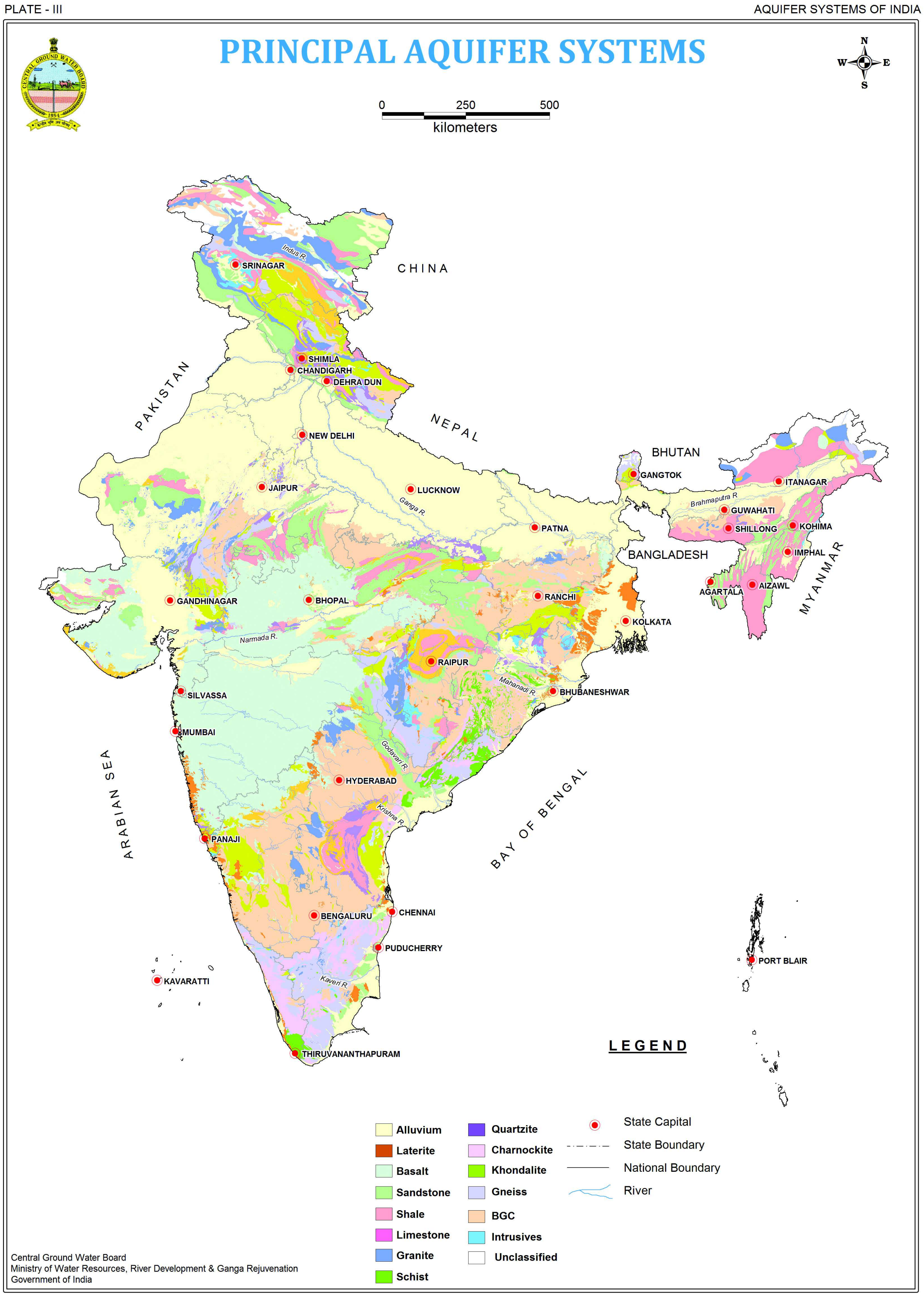

Fig. 1: The aquifer systems of India (adopted from CGWB 2012; Saha *et al.* 2016)

water level in many parts of India. The decline is noticeable mostly in parts of Rajasthan, Punjab, Haryana, Gujarat, Delhi, Karnataka and Tamil Nadu states (Chinnasamy and Agoramoorthy 2015; Saha and Ray 2019). Besides, there is a serious dimension of groundwater contamination both from geogenic and anthropogenic sources.

This kind of dependence on groundwater sources and the aquifer response has motivated Indian and International workers for a detailed study of various aspects of Indian hydrogeology. The objective of this article is to present a review of the recent research on hydrogeology in India. In context of this, we have discussed the various researches carried out in previous five years (between 2014 and 2019 March) under different themes. The theme-wise discussion is as follows.

Groundwater Quality

Groundwater quality assessment, mobilization process of different contaminants is an integral part of any hydrogeological study and it is becoming important on account of the fact that it has direct effects on human health. It is one of the widely researched aspects of hydrogeology and widely studied. Significant scientific contributions have been made in this field in recent years, across the country. Significant studies on the factors controlling groundwater quality assessment, hydrochemicalfacies evolution, heavy and trace elements distribution and its linkage to the geogenic and anthropogenic forcing were accomplished in the flood plains of the river Yamuna and parts of the National Capital Region of Delhi (Sarkar and Shekhar 2015; Sarkar *et al*. 2016a; Sarkar *et al*. 2016b; Sarkar *et al*. 2017; Sarkar and Shekhar 2018).

Significant studies on water quality were carried out in many parts of India. This includes studies by Jeelani *et al*. (2014) conducted in Kashmir valley; Bokaro district, Jharkhand by Singh *et al.* (2018a); Chottanagpur Plateu by Gautam *et al*. (2015) Panna district, Madhya Pradesh by Kumar *et al*. (2016a); in Manipur by Thockchom and Kshetrimayum (2019); in Barak valley region of Assam by Khangembam and Kshetrimayum (2019); southern Gangetic plain of Bihar by Sethy *et al*. (2017). Duttagupta *et al*. (2019) have studied faecal pollution in groundwater in Indo- Ganga-Brahmaputra basin.

Similar groundwater quality studies were carried out in parts of Nalagarh, valley, Himachal Pradesh by Herojeet *et al*. (2016). Various parts of Gujarat were studied by Kahtri *et al*. (2016); Patel *et al*. (2019). Similar studies were undertaken for Punjab by Thakur *et al*. (2016) and Kaur *et al*. (2017).

The water quality of River Garra at Shahjahanpur, Uttar Pradesh was studied by Khan *et al*. (2016a). The Groundwater quality issue in arid and semi-arid region of Rajasthan state and their vulnerability has been assessed and possible remedial measures were also discussed Ahadaand Suthar (2017); Chaudhary and Sathees Kumar (2018) and Gupta and Sharma (2018).The water quality index based assessment of groundwater quality for Varanasi was accomplished by Chaurasia *et al*. (2018) and the nitrate contamination in the groundwater of Varanasi was assessed by Ahamad *et al*. (2018). Similarly, the anthropogenic influence on the groundwater quality of the shallow aquifers was studied by Saba *et al*. (2018). The trace elements and heavy metals in parts of Uttar Pradesh were investigated by Kumar *et al*. (2019b). Khan and Umar (2019) studied the environmental risk assessment of coal fly ash on soil and groundwater quality in Aligarh district of Uttar Pradesh. While Duggal *et al*. (2017a) assessed the metal contamination in groundwater.

Assessment of trace elements and heavy metals in groundwater was also carried out by few researchers, in Cauvery delta, Tamil Nadu (Vetrimurugan *et al*. 2017a; Elumalai *et al*. 2017), Ambur, Tamil Nadu (Kanagaraj *et al*. 2016) and in Bhima basin of Karnataka state (Manoj *et al*. 2017). Statistical tools were also used to interpret the hydro-geochemical data by many researchers in different parts of South India, Chitoor, Andhra Pradesh (Nagaraju *et al*. 2016), at Thamirabharani basin, Tamil Nadu (Magesh *et al*. 2017), in Bengaluru, Karnataka (Gulgundi and Shetty. 2018), in Nagpur, Maharashtra (Marghade *et al*. 2015). Studies on geological, geomorphological controls over water quality were carried out in Tirunelveli, Tamil Nadu (Senthilkumar *et al*. 2015), at Nalgonda, Telengana (Rajaveni *et al*. 2017) and in Central Kerala (Sreekala *et al*. 2018).

Water quality assessment based on major ions have been extensively carried out in southern India such as in Tamil Nadu at Nagapattinam

(Gnanachandrasamy *et al*., 2015), Tiruchirappalli (Asoka *et al*. 2017), Tiruvallur (Senthil Kumar *et al*. 2017), South Chennai (Kanagaraj *et al*., 2018a), Thamirabharani basin (Magesh *et al*., 2017), Cauvery basin (Ramya Priya and Elango 2018), Amravathy basin (Ahamed *et al*., 2015), in Puducherry (Keesari *et al*., 2016), in Bhima basin (Thirumurugan *et al*., 2018), in Kerala at Meenachil basin (Vincy *et al*., 2015), Palakkad (Kumar *et al*., 2016b; Shaji *et al*., 2018), Allapuzha (Manjusree *et al*., 2017), Trivandram (Thompson *et al*., 2018), Kollam (Maya *et al*., 2018) and in the state of Andhra Pradesh at Cuddapah (Dar *et al*., 2015). Integrated assessment of groundwater involving chemical, microbial and antibiotic susceptibility studies after the December 2015 extreme floods in Chennai were also carried out by Gowrisankar *et al*. (2017a).

Arsenic contamination of groundwater and its impact on human health and its pathways into agriculture products has been intensely studied by Kumar *et al*. (2017a) in Naogaon district of Assam. He has opined that arsenic is sourced from argo-chemicals applications. Similar studies have been carried out for Manipur valley by Chandrashekhar *et al*. (2016) and Gupta and Singh (2018) and in Puducherry by Sridharan and Nathan (2018). Kumar *et al*. (2018d) studied arsenic contamination on opposite banks of Ganga River in its lower reaches. Mahanta *et al*. (2015), Verma *et al*. (2015 and 2016) and Choudhary *et al*. (2017) have investigated arsenic distribution in the Brahmaputra plains. Arsenic along with other trace elements in groundwater and in dietary components have been studied in Samastipur and Patna district of Bihar by Kumar *et al*. (2016a) and Chakraborti *et al*. (2016) respectively. Arsenic in groundwater is emerging as a major research focus in parts of Uttar Pradesh, the occurrence and mobilization of arsenic in groundwater has been widely investigated by various workers (Khan *et al*. 2016b; Chakraborti *et al*. 2018; Singh *et al*. 2018b; Mukherjee *et al*. 2018a; Olea *et al*. 2018; Singh *et al*. 2018c). Elevated level of arsenic was also reported in groundwater of district Murshidabad, West Bengal (Sankar *et al*. 2014).

Fluoride is the most widespread geogenic contamination in India. Ali *et al*. (2019); Ali *et al*. (2016) and Podgorski *et al*. (2018) have done significant work in assessing the global fluoride distribution and its vulnerability analysis. Specific area based fluoride contamination studies have been carried out in parts of Haryana by Ali *et al*. (2018); Singrauli area of Madhya Pradesh by Usham *et al*. (2018). A detailed account of fluoride contamination in Rajasthan has been produced by Choubisa (2018). The fluoride pollution in groundwater of different parts of Uttar Pradesh was studied by Sahu *et al*. (2018).

In southern India fluoride pollutant were investigated in Tamil Nadu at Dharmapuri (Jagadeshan *et al*., 2015; Jagadeshan and Elango 2015), Tuticorin (Selvam 2015), Madurai (Thivya *et al*., 2017), Chennai (Nair *et al*., 2016) in Allepey, Kerala (Raj and Shaji 2017) in several regions of Andhra Pradesh (Hallett *et al*., 2015), at Medak, (Adimallah and Venkatayogi *et al*., 2017), Basara (Narsimha and Sudhrashan 2017a; Narsimha and Ranjitha2018; Adimallah and Venkatayogi 2018), Siddipet (Narsimha and Sudhrashan 2017b), Nirmal (Adimallah *et al*., 2018a), Ongole (Rao *et al*., 2017), in Telangana at Nalgonda (Rajesh *et al*. 2015; Rao *et al*., 2016; Madhnure *et al*., 2018) Peddavagu (Adimallah *et al*., 2018b), Maheswaram (Pauwels *et al*., 2015) in Yavtmal, Maharashtra (Marghade *et al*., 2019) and in Madhya Pradesh (Singh *et al*., 2018d).

In recent years, uranium and radon as emerging contaminants are reported from various parts of India and reported by Kumar *et al*. (2018b) in Patna district of Bihar; Jammu district by Ajay *et al*. (2016); Singh *et al*. (2014) in western Haryana state and Duggal *et al*. (2017b) from western part of Haryana; Kaur and Mehra (2018) in Solan district of Himachal Pradesh; Singh *et al*. (2016) from Shimla area of same state. High radon in groundwater has been reported from Faridabad, Haryana state by Singh *et al*. (2019) and by Singaraja *et al*. (2016); from Udhampur district, Jammu and Kashmir by Kumar *et al*. (2018a). Similar studies of high uranium in groundwater and its impact on human health in Punjab has been carried out by Bajwa *et al*. (2017), Narang (2018), Sharma *et al*. (2018) and Sharma *et al*. (2019). In Bhima basin by Manoj *et al*. (2017) in Karnakata. No significant radon hazard has been detected in Rajasthanby Mittal *et al*. (2016).

The national capital region of Delhi is largely dependent on groundwater for its domestic use. Number of researchers have worked on chemical quality of groundwater and impact of urbanization (Rai and Saha 2015; Parween *et al*., 2017; Singh *et al*., 2017). The impact of waste dumping on groundwater quality and biodiversity on water bodies in Bramaputra plain has been described by Choudhary and Gupta (2017). Similarly, impact of landfills has been studies in the urban areasof Ranchi, Jharkhand as described by Chakraborty and Kumar in 2016.

The impact of coal mining on groundwater has been investigated in Chhattisgarh state by Dhakate *et al*. (2019) and in Bankura district of West Bengal by Adhikari and Mal (2019). In a significant study in east Singhbhum district, Singh *et al*. (2018a) studied the quality of groundwater produced during production of coal bed methane. Impact of acid mine seepage has been carried out by Mohanty *et al*. (2018) in Ramgarh district of Jharkhand state. Behera and Das (2018) have applied multivariate statistical analysis to understand chemical quality and Khan and Jharia (2018) have studied groundwater quality in parts of Chhattisgarh district. In an interesting study by Shah *et al*. (2018) chemical quality of groundwater in Dholera field of Gujarat has been studied.

The impact on land use of groundwater quality was investigated in NOIDA-Faridabad region (Sarkar *et al*., 2016a) and in west Ganga basin (Khan *et al*., 2017). Managed Aquifer Recharge (MAR) techniques are popularly used method to mitigate groundwater contamination problems. Lowering the solute concentrations by MAR was carried out in several regions of Tamil Nadu in Arani river basin by check dam (Parimalarenganayaki *et al*., 2015; Parimalarenganayaki and Elango 2016). Studies on percolation pond was also carried out by Massuel *et al*. (2014) in Sangamupur, Andhra Pradesh, Boisson *et al*. (2015a) in Maheswaram, Telanganaand by Christy and Lakshmanan (2017) in Tamil Nadu. Mitigation of the problem of fluoride rich groundwater by dug well recharge method was studied in Dharmapuri, Tamil Nadu (Brindha *et al*., 2016) and by check dam method in Pambar river basin, Tamil Nadu (Gowrisankar *et al*., 2017b). A new Fluoride Index to mitigate geogenic contamination by Managed Aquifer Recharge (FIMAR) was brought out to overcome the fluoride problem by long-term hydrogeochemical studies (Kalpana *et al*., 2019).

Stable and Environmental Isotope-based Investigations

Various stable and environmental isotopes have been widely used to address wide ranging groundwater issues. It helps immensely to understand the aquifer character, recharge processes, and inter-aquifer interaction of water in case of multi layered aquifers and age of groundwater. Bhat and Jeelani (2018) have used stable oxygen and hydrogen isotopes and other chemical signature to understand surface and groundwater interaction in watersheds of Kashmir and also in Dal Lake area by Saleem and Jeelani (2017).

Thakur *et al*. (2018a) have undertaken similar study in the intermontane valley of Una, Himachal Pradesh. The impact of coal mining in groundwater regime has been investigated in Chhattisgarh by Dhakate *et al*. (2019). It is always observed that the shallow and deeper aquifer in Indo-Ganga-Bharhaputra Plains have different recharge mechanisms. Debnath *et al*. (2019) has studied the isotopic signature change in tidally influenced groundwater in Bay of Bengal. Keesari *et al*. (2017) has studied the recharge processes of the shallow and deeper aquifers of Punjab using stable isotopic characteristics. Similar studies have been carried out by Shah and Umar (2017) in Ganga basin in parts of Uttar Pradesh. The variation in isotopic signatures of North West India were used by Joshi *et al*. (2018) to understand the recharge processes operational at regional level and characterize the groundwater dynamics. Similarly, Sarkar *et al*. (2017) observed that in comparison to groundwater samples from the active Yamuna flood plain of Delhi, the stable isotopic signature in the older alluvium plain showed distinct deviation from the global meteoric line. Boron isotopes were also used to understand the evolution of thermal springs (Chandrasekhar *et al*. 2018). Further, Kanagaraj and Elango (2019) have also used chromium isotopes to understand the source of contaminants in groundwater.

Remotely Sensed Data Application and Vulnerability Analysis

Remotely sensed visual, electromagnetic and micro gravity data are been used for addressing various issues of groundwater targeting, mapping of aquifers, monitoring and assessment of groundwater resources.

The remotely sensed data analysis is often carried out in GIS platform to express the spatio-temporal variability. The water level was estimated by analysis of remote sensing data by Kaur and Rishi (2018) in Panipat district of Haryana. Groundwater prospective zones are mapped by Thakur *et al*. (2018b) in parts of Himachal Pradesh. In a interesting study, Guleria *et al*. (2019) has applied GIS to investigate migration of contaminant plume in Punchkula Region of Haryana.

The DRASTIC analysis in a GIS environment is a useful tool for understanding and analysis of the vulnerability of groundwater system. Saha and Alam (2014) had applied DRASTIC and Pesticide DRASTIC in Nalanda district of Bihar. Similar studies have been taken up by Ghosh *et al*. (2015) in Katri watershed district Jharkhand and Kodagnar watershed, Tamil Nadu by Mondal *et al*. (2017). The groundwater quality distribution and its suitability in a spatial scale have been analyzed by application of GIS for the state of Rajasthan by Tiwari *et al*. (2017). A similar efforts has been made in Doon valley by Jasrotia *et al*. in 2018. Groundwater suitability zonation were also identified in several regions at Tamil Nadu (Murthy *et al*., 2015; Jothibasu and Anbazhagan 2018) and in Karnataka (Seyedmohammadi *et al*., 2016). Fuzzy techniques and geostatistical tools were also utilized to assessed groundwater suitability in several regions of Southern India (Raj *et al*., 2016; Magesh *et al*., 2018). Lapworth *et al*. (2018) have studied urban groundwater vulnerability using organic contaminants and tracers.

Studies on identification of groundwater potential zones were also carried out in Tamil Nadu at Upper Odai basin (Anbazhagan and Jothi Basu 2016), Ponnaiyar basin (Jothi Basu *et al*., 2016), Salem (Maheswaran *et al*., 2016), Vellore, (Kanagaraj *et al*., 2018b), in Kuttiyadi river basin (Swetha *et al*., 2017). The site specific groundwater recharge structures in GIS environment were studied by Kaliraj *et al*. (2015).

Application of micro gravity variation data available from GRACE mission is being amply applied by researchers in addressing groundwater issues particularly on its storage change and its ramifications. The GRACE data along with in situ observations have been used by Bhanja *et al*. (2019) to assess usable groundwater storage in India as well as long term groundwater recharge rate for entire country (Bhanja *et al*. 2018; Bhanja and Mukherjee 2019). In a significant study, Bhanja *et al*. (2017a and 2017b) have indicated groundwater resource rejuvenation in parts of India; the reason has been attributed to large scale artificial recharge and rainwater harvesting intervention through government policies. Similar studies by Bhanja *et al*. (2016) applied the GRACE data to assess groundwater storage variability in India.

Coastal Hydrogeology

The coastal aquifers, particularly where the alluvial aquifers are extended towards beneath the sea there is always an apprehension of saline water intrusion, if there is unabated pumping of fresh groundwater which flows on saline water in coastal region. In a significant study by Mohanty and Rao (2019), the chemical and isotopic parameters of groundwater have been used in Puri district located at the Bay of Bengal in Orissa state. The study indicates that the fresh groundwater in these coastal regions is subjected to the continuous influence of seawater mixing, dissolution of carbonate phase minerals, aided with rock-water interaction, and ion exchange processes are the significant governing factors, which controls the groundwater evolution.

Sea water intrusion is one of the major groundwater management problems of southern India. Declining water levels in the coastal regions have led to sea water intrusion into the aquifers in most of the regions. Detailed studies on sea water intrusion in aquifers of northern and southern Chennai has been carried out (Senthil Kumar *et al*., 2017). Geochemical methods (Nair *et al*., 2015), electrical resistivity techniques (Sathish and Elango 2016), major ions chemistry (Samantara *et al*., 2017) and groundwater modeling techniques have been utilized to decipher the extent of sea water intrusion in Chennai, Tamil Nadu. Studies on changes in groundwater quality with respect to sea level change in Kerala werecarried out by Sreekash *et al*. (2018). Submarine groundwater discharge studies have also been carried out in Southern India at Kerala (George *et al*., 2018) and in Coleeroon estuary of Tamil Nadu state (Prakash *et al*., 2018).

Assessment and Management of Groundwater Resources

Though the overall Stage of Groundwater

Development in India is 62%, large swath of the country, particularly in north-western and southern peninsular region of India is marked with over-exploitation of this replenishable resource. In eastern part of India, where Stage of Groundwater Development otherwise remain within safe limit, the urban areas are often affected by groundwater over-exploitation and water level decline because of heavy concentrated pumping. In one such area in Indo-Gangetic Plain, around Patna city, Saha *et al*. (2014) have studied the impact of urban pumping on groundwater regime. A gradual decline in water level had been reported. Estimation of recharge to groundwater was assessed through several techniques by different researchers like daily groundwater level observation data (Parimalarenganayaki and Elango 2018), remote sensing techniques by considering rainfall and landuse/landcover changes (Kirubakaran *et al*. 2018; Purandhara *et al*. 2018), isotope/mass balances (Hameed *et al*. 2015), water balance technique (Sarah *et al*. 2014; Boisson *et al*. 2014), groundwater modelling techniques (Sashikumar *et al*. 2017), recharge through ungauged watersheds (Santhanam and Abraham 2018) and also using MAR technologies (Prathapar *et al*. 2015). Groundwater requirements for agricultural purposes were also identified using satellite data for Telangana state (Ferrant *et al*. 2017). Jeelani *et al*. (2017) studied hydrogeological processes in the aquifers located in glaciated high altitude zones of Himalayas. In another study, the same team (2017) had estimated the recharge in karst spring in snow dominated western Himalayas. A study on participatory framework for managing groundwater resources throughout the country were carried out by Kulkarni *et al*. (2015). The importance of groundwater in virtual water studies have been highlighted by Sreevidhya and Elango (2019).

The assessment of the groundwater balance, resource estimation and management policies based on sound scientific study have always been back bone of the research with the societal relevance. Saha *et al*. (2016) has produced a detailed account of groundwater resource availability and management options in the Ganga Basin covering India, Bangladesh and Nepal. A good amount of recent research has been done in the National Capital Region (NCR) of Delhi. Kumar *et al*. (2018c) presented a holistic perspective of the whole NCR Delhi and opined that the localized high yielding aquifers could be exploited judiciously for mitigation of any possible drinking water crisis. Sarkar *et al*. (2016a) presented a holistic glimpse of the groundwater environment of Delhi and also opined that the groundwater regulation measures in Delhi are showing positive results. Similarly, Shekhar *et al*. (2015) proposed for scientific dewatering of the shallow aquifers coupled with planned replenishment for meeting the drinking water need. Chatterjee *et al*. (2018) had studied in detail the groundwater balance of a watershed in east Rajasthan state arid area and proposed the management options.

Aquifer Mapping

The aquifer geometry and connectivity is the most fundamental control on the occurrence and movement of the groundwater. The past hydrogeological investigations in India were mostly restricted to the delineation of the aquifer geometry and its characterization considering aquifers as a single unit in an area. Ever increasing groundwater extraction and large-scale over-exploitation has initiated and understanding the groundwater resources should be used sustainably. For this a complete and detailed understanding of aquifer system, its resource availability and quality status is essential. On the basis of that the supply and demand side interventions can be framed so that the groundwater resource can be used optimally. Saha *et al*. (2019) havepenned the objectives, methodologies and outputs of National aquifer mapping and Management Programme taken up by Central Ground Water Board, India. Saha *et al*. (2017) had discussed about issues on groundwater management in India. For the aquifer system of North West India, a significant increment to the scientific knowledge was made by Dijk *et al*. (2016). They proposed that in contrast to the classical layer cake models of the regional aquifer stratigraphy, it was the ribbons of sand in a framework dominated by fine sand and silt together with clay lenses which defined the heterogeneity and anisotropy of the aquifer. Further they opined that the regional aquifers of the North West India had high vertical connectivity and low lateral connectivity in the top 200 m. Mukherjee *et al*. (2015) has delineated the aquifer systems of India and its neighboring countries. In another study, Bonsor *et al*. (2017) studied hydrogeological typologies of the Indo Gangetic plain. MacDonald *et al*. (2016) in an elaborate study assessed the groundwater depletion and quality deterioration in the Gangetic Plains

Groundwater Modeling

The system simulation and numerical modeling of the groundwater system is a sophisticated high end hydrogeological tool to understand the groundwater system, associated hydrological processes and foresee the system response under different possible scenarios. Groundwater modeling is a time consuming activity and thus the number of research publications are limited. In recent years, Soni *et al*. (2018) estimated that the recharge into the groundwater system of the Palla flood plain of Delhi can sustain yield of about 100 MCM of water per year. Groundwater modeling related to quantity aspects in relation with overdraft and climatic change were carried out by few researchers at various regions of South India, at Berdampur, Karnataka (Lathashri and Mahesha 2016) and at Nagapattinam, Tamil Nadu (Gopinath *et al*. 2016). Modelingaquifer responses to varying groundwater pumping rates, climate change and sea level rise in regions such as South and North of Chennai, Tamil Nadu were carried out by many workers (Rajaveni *et al*. 2015; Sathish and Elango 2015; Rajaveni *et al*. 2016; Sathish and Elango 2019). The impact of climate change on groundwater extraction in Kudaliar catchment, Andhra Pradesh was modeled by Ferrant *et al*. (2014).

Geochemical modeling studies were carried out by many researchers to identify the hydrochemical process responsible for major and minor ions in groundwater at Tirupattur, (Kumar *et al*. 2015) and also in Andhra Pradesh (Marie *et al*. 2014). Solute transport model in Cauvery delta was studied by Vetrimurugan *et al*. (2017b) and nitrate contamination in groundwater of Berampadi, Karnataka was studied by Bhuvaneshwari *et al*. (2018).

Hydrogeological Processes, Well Hydraulics and Land Subsidence

The understanding of the hydrogeological processes and well hydraulics is an important aspect of the hydrogeological research. Stream aquifer interaction is an important aspect in context of the holistic water resources research. In this context; Shekhar (2016) have established the importance of base flow as an integral part of the environmental flow of a River. Further, hydraulic investigation was performed in southern India by Boisson *et al*. (2015b).

In a significant study, Mukherjee *et al*. (2018b) have dealt on reducing summer flow of the river Ganga due to extensive over-exploitation of groundwater of the floodplain aquifers. While Soni *et al*. (2014) opined that the adherence to the monsoon environmental flow is a necessity for replenishment of the flood plain aquifers. The relatively low stream power of River Yamuna having direct effect on the River morphology of the middle stretch has also been attributed to the excessive groundwater withdrawal along these reaches and the catchment (Bawa *et al*. 2014). It has been established that the efficient conjunctive use of surface and groundwater in the overexploited aquifers can prevent seasonal drying up of the non-glacier linked Rivers (Shekhar *et al*. 2018). River bank infiltration can be used effectively for water supply for the urban areas located on suitable aquifer system on the bank of river. Indwar and Ghosh (2018) had carried out the study on the efficacy of river bank infiltration on the aquifers in Haridwar areas of Uttarakhand. Artificial recharge techniques were also used to improve groundwater quality in Salem region (Subburaj *et al*. 2018).

Further, Jain and Shekhar (2019) estimated the regional groundwater flow converging into the aquifers of the Palla area of Delhi as approximately 11 MCM/year and base flow contribution to the River Yamuna in this stretch is about 0.5 MCM/year. Kumar *et al*. (2019a) established the geomorphic control on occurrence of groundwater and accounted for the recent disappearance of streams in the central part of Tarai region in Uttarakhand. Kumar *et al*. (2017b) presented the aquifer parameters of unconfined aquifer in the flood plain of Delhi on the basis of long duration pumping test and their experimentation confirmed the fact that regulated pumping over a decade from the Palla well field of Delhi has improved the groundwater quality over time.

Land subsidence is a major geological issue and it observed in thick alluvial aquifer areas where rapid water level decline is taking place. Though there are many glaring examples of land subsidence around the world. In India, it is getting reported in its initial stage from few urban areas. Choudhary *et al*. (2017) has assessed land subsidence in Gandhinagar, Gujarat state by GPS measurement and assessed the rate of subsidence at 5 mm per year.

Geophysical Investigations

There is considerable application of different geophysical techniques for targeting, delineating and characterizing aquifers. The sea water intrusion in the coastal aquifers has been studied through a 3 dimensional variable density conceptual phreatic model. Rao *et al*. (2018) have delineated the groundwater prospective zone from the delta region of Vasista Godavari River by carrying out extensive vertical electrical sounding with co-lateral interpretation of existing lithologs and water quality data. Ravindran *et al*. (2016) have delineated and assessed the groundwater resource in Holocene deposit in Gulf of Mannar coast of southern India by applying 2-D electrical resistivity tomography, hydrochemical and granulometrical studies. Sonkamble *et al*. (2016) have integrated electrical parameters, hydrochemistry, topography and water table to decipher the geometry of fresh water land at Cuddalore coast India. In a pioneer work by Nicolas *et al*. (2019) recharge dynamics in weathered of crystalline rocks of Peninsular India was delineated. In a significant study by Chandra *et al*. (2019) they reviewed and assessed the application of airborne electromagnetic survey and delineating the fractured aquifer in the hard rock aquifer in India.

Conclusions

Groundwater, which is the most critical natural resource in India, is being extracted at a rate of about 250 km^3 annually. Groundwater is the lifeline for irrigation and drinking security in India. Commensurate to its huge societal importance, a wide range of research is taking place in hydrogeology, ranging from investigation, assessment, monitoring, geographical variation in its occurrence, mapping of aquifers, environmental implications on its development etc. There are several studies on the assessment and the deterioration in the quality of groundwater, remediation of contaminated groundwater and application of remote sensing for targeting, monitoring and assessing the resource. Since the resource is dynamic in nature, as its gets recharged in an annual scale, mainly due to monsoon, its exploitation should remain within the annually recharged volume, so that the resource is utilized in a sustainable manner. However, in many parts of India, the annual extraction is exceeding the annual recharge, resulting in over-exploitation of aquifers, rendering serious implication on ecology and environment and lively hood. Wide array of research are taking place in that direction. The community should take an active role on its sustainable management.

This paper highlights findings and outcomes of about 280 papers published in International peer reviewed journals. Considering wide varieties of research, the outputs were discussed under (i) Groundwater quality, (ii) Stable and environmental isotopes-based investigation, (iii) Remotely sensed data application and vulnerability analyses, (iv) Coastal hydrogeology, (v) Assessment and management of groundwater resources, (vi) Aquifer mapping, (vii) Groundwater modelling, (viii) Hydrogeological processes, well hydraulics and land subsidence and (ix) Geophysical investigations. Thus this paper gives a glimpse on recent research studies on groundwater in India and this will help in laying the roadmap for future research in wide arena of hydrogeology.

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