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ORIGINAL ARTICLE

Impact of climate change on groundwater hydrology: a comprehensive review and current status of the Indian hydrogeology

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Abstract

Groundwater is the second largest store of freshwater in the world. The sustainability of the ecosystem is largely dependent on groundwater availability, and groundwater has already been under tremendous pressure to fulfill human needs owing to anthropogenic activities around various parts of the world. The footprints of human activities can be witnessed in terms of looming climate change, water pollution, and changes in available water resources. This paper provides a comprehensive view of the linkage between groundwater, climate system, and anthropogenic activities, with a focus on the Indian region. The significant prior works addressing the groundwater-induced response on the climatic system and the impacts of climate on groundwater through natural and human-instigated processes are reviewed. The condition of groundwater quality in India with respect to various physicochemical, heavy metal and biological contamination is discussed. The utility of remote sensing and GIS in groundwater-related studies is discussed, focusing on Gravity Recovery and Climate Experiment (GRACE) applications over the Indian region. GRACE-based estimates of terrestrial water storage have been instrumental in numerous groundwater studies in recent times. Based on the literature review, the sustainable practices adopted for optimum utilization of groundwater for different purposes and the possible groundwater-based adaptation strategies for climate change are also enunciated.

Keywords Groundwater · Climate change · Water quality · Groundwater pollution · GRACE · Sea-level rise

Background

Groundwater is the second largest freshwater resource on the planet and meets above one-third of global drinking water demands (Li 2016). In India, a majority of irrigation water and domestic water supplies are fulfilled by groundwater. In the USA, almost two-fifths of the domestic water supply is met through groundwater. Almost all the rural residents in the USA depend on groundwater for drinking purposes (NRC, 2000). Hence, regardless of whether a developed, developing, or an underdeveloped country, groundwater plays a vital role in fulfilling basic needs. The population explosion, polluted surface water bodies, and growing climatic uncertainties are expected to cause an increased dependence on groundwater in the future. Moreover, groundwater pollution has risen as a major issue, which is getting aggravated day by day, as evident from several recent studies (Adimalla and Taloor 2020; Aladejana et al. 2020; Cuthbert et al. 2019; Green 2016; Hamed et al. 2018; Jasrotia et al. 2019; Khalaj et al. 2019; Li 2016; McGill et al. 2019;

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Morsy et al. 2017; Taloor et al. 2020). Further, the impacts of climate change and variabilities have risen as challenging issues to the present generation, which are likely to worsen in the future due to anthropogenic interventions with nature (Guptha et al. 2021 and 2022; Swain et al. 2022a, b).

The public water supply is likely to be more dependent on groundwater in the future due to population growth and looming climatic variability (Li et al. 2016 and 2017). Recently, groundwater pollution has become a major concern due to possible impacts on human and animal health and ecological consequences. Several studies have reported deterioration in groundwater quality, mainly caused by the application of pesticides and fertilizers (Adimalla et al. 2018a; Adimalla et al. 2020; Gupta 2020; Gupta and Sharma 2019; Khalaj et al. 2019; Li et al. 2014; Zaveri et al. 2016). This leads to nitrate contamination of groundwater, causing fatal diseases in human beings. Not only for human beings, but all the living species that depend on groundwater are also affected by the harmful effects of groundwater quality changes (Morsy et al. 2017).

Influence of climate on groundwater systems

Climate change and variability have both direct and indirect effects on groundwater systems. The direct impacts include the effects on natural recharge mechanisms. The precipitation (P) and evapotranspiration (ET) are largely governed by climate and land cover, whereas the geology and soil dictate if a water surplus (P–ET) can be transmitted and stored in the subsurface (Taylor et al. 2013a). The global diffuse recharge is estimated to be 0.013 to 0.015 Mkm^3 per year (Döll and Fiedler 2008; Wada et al. 2010), which is almost 30 percent of renewable freshwater resources globally (Döll 2009). However, these are not measured contributions to aquifer as these are modeled estimates representing potential recharge fluxes, i.e., P minus ET. Hence, their spatial variation is linked mainly to the global precipitation distribution. Moreover, the focused recharge is not included in these modeled estimates, which may be vital for semi-arid environments.

The climatic variability along with the extremes (droughts/floods) have pronounced impacts on groundwater recharge. The extremes are often linked to large-scale atmospheric oscillations, viz. El Niño/Southern Oscillation, Atlantic Multidecadal Oscillation, Pacific Decadal Oscillation, etc. (Taylor et al. 2013b; Treidel et al. 2011). During 2000–07, the extreme droughts over Murray–Darling basin, Australia, caused a substantial decline in groundwater storage, owing to a sharp decrease in recharge (Leblanc et al. 2009). On the other hand, the recharge in boreholes of tropical Africa is disproportionately contributed by extreme rainfall events (Owor et al. 2009; Taylor et al. 2013b). The heavy rainfall events often act as the sole contributor to groundwater recharge in semi-arid regions (Döll and Fiedler 2008; Small 2005), and they mostly generate focused recharge beneath ephemeral surface water bodies (Favreau et al. 2009; Pool 2005; Taylor et al. 2013b). Further, recharge from extreme precipitation events is often responsible for microbial pollution of the shallow aquifer. This causes diarrhoeal diseases in several countries where water supplies are dependent on shallow aquifers (Taylor et al. 2009). Scanlon et al. (2005) assessed the ecological controls on water-cycle response to climate variability in deserts and found the vegetation dynamics to be highly influential. Alterations in snowmelt regimes lead to a reduction in the magnitude and seasonal duration of recharge at high latitudes and elevations (Sultana and Coulibaly 2011; Tague and Grant 2009; Kumar et al. 2021a; Sood et al. 2020 and 2021a, b; Singh et al. 2021). The peak and low groundwater level (GWL) show a shift in magnitude and timing for aquifers in valleys (Allen et al. 2010). Figure 1 represents a conceptual diagram of the natural impacts of climate change on the groundwater system, which does not consider the role of anthropogenic activities.

The indirect impacts of climate variability on groundwater systems are mostly changes in groundwater use, governed by anthropogenic activities. In contemporary times, the land-use changes, specifically the expansion of agricultural fields, are responsible for complicating the relations between groundwater and climate (Bahita et al. 2021a; Taloor et al. 2021; Yadav et al. 2020). The natural ecosystems and managed agro-ecosystems exhibit diverging responses to changes in rainfall and sometimes, the terrestrial hydrology

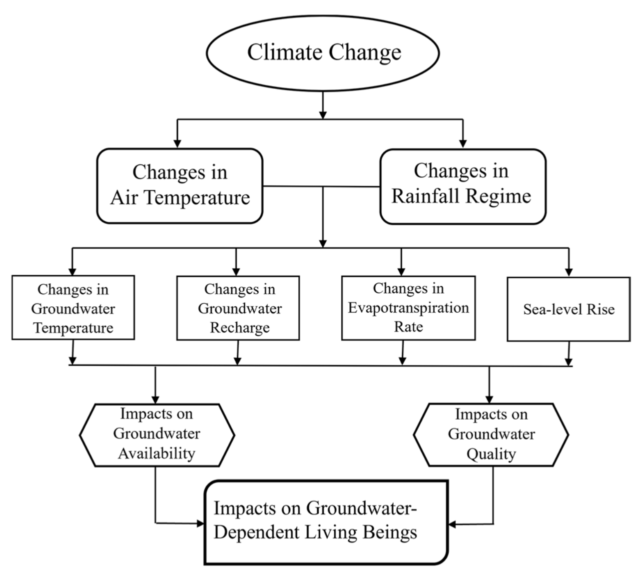

Fig. 1 Conceptual diagram of natural impacts of climate change on groundwater system

may be more influenced by land-use changes than climatic changes. Enhanced runoff through focused recharge by ephemeral ponds and soil crusting due to conversion of savannah to cropland led to an increase in groundwater recharge and storage during multi-decadal droughts over the Sahel region, West Africa (Leblanc et al. 2008). Similarly, land-use changes from natural ecosystems to rainfed agricultural lands in the southwest US and southeast Australia increased the groundwater recharge in the early-twentieth century. However, the salinity of unsaturated soil profiles associated with this recharge caused degradation in groundwater quality (Scanlon et al. 2006). The recharge rates under agricultural lands exhibited a significant increase compared to the native perineal vegetation over these regions (Cartwright et al. 2007; Leblanc et al. 2012; Scanlon et al. 2010).

As of 2000, nearly 90% of consumptive water use and almost 70% of freshwater withdrawals globally were dedicated to irrigation, which reflects the huge influence of human activities on the terrestrial hydrologic system (Döll et al. 2012). The impacts can be broadly put as: (a) groundwater recharge resulting from return flows due to surface water irrigation; (b) depleted groundwater levels in areas of mainly groundwater-dependent irrigation; and (c) surface-energy budget alterations connected with irrigation-induced increase in soil moisture. Irrigation has led to a depletion of groundwater due to intense abstraction in arid and semi-arid regions of the world, e.g., US High plains (Longuevergne et al. 2010; Scanlon et al. 2012a), Northwest India (Rodell et al. 2009), and North China (Chen 2010); and in humid regions, e.g., Bangladesh (Shamsudduha et al. 2012), and Brazil (Foster et al. 2009). The source of irrigation shifted to groundwater from surface water during the persistent drought of 2006–09 over the California Central Valley, which resulted in a severe decline in groundwater levels (Famiglietti et al. 2011; Scanlon et al. 2012a,b). Irrigation through surface water since the 1960s led to an increase in groundwater recharge by seven times over parts of the valley (Faunt 2009). The enhanced recharge hampers the groundwater quality by flushing natural pollutants such as Arsenic from the groundwater system (Shamsudduha 2011; Van Geen et al. 2008) and by mobilizing salinity from unsaturated soil profiles (Scanlon et al. 2006). Hence, the indirect impacts of climate change may be more pronounced than the direct impacts on groundwater systems.

As the surface water systems are enormously affected by climate, the importance of groundwater as a reliable resource of freshwater has become increasingly critical, especially for societal water security. Groundwater often seems to be unaffected by the direct impacts of climate change as it is beneath the ground. Nevertheless, climate change affects the groundwater over the long term through several pathways (Green et al. 2011; Taylor et al. 2013a). Different physical, geochemical, and transport processes, viz. irrigation, fertilization, volatilization, nitrification, denitrification, mineralization, nitrate leaching, advection, dispersion, diffusion, etc., contribute to groundwater pollution directly or indirectly (Li 2016). Several studies (Babiker 2004; Obeidat et al. 2013; Spalding and Exner 1993) have provided evidence of increasing pesticide and nitrate concentrations in groundwater across different parts of the world, although it can be mainly due to anthropogenic activities. However, land-use changes causing warmer temperatures may lead to earlier and extended growing seasons. It may also enable favorable conditions for crops requiring high pesticide and fertilizer applications (Bloomfield et al. 2006; Li and Merchant 2013). The increasing temperature may also result in lower soil organic matter and enhanced denitrification, encouraging higher fertilization application (Dalias et al. 2001; Li 2016; Rivett et al. 2008; Zhu and Fox 2003). Jean et al. (2006) described the role of extreme precipitation events in increasing the microbial pollution of groundwater through flooding wells. In general, changes in rainfall and temperature affect the groundwater recharge causing shifts in groundwater levels and changes in leachate transport (Ali et al. 2012; Eckhardt and Ulbrich 2003; Scibek and Allen 2006). Similarly, reduced precipitation coupled with rising temperature may increase the size and frequency of crack formation in soils, leading to increased contamination (Bloomfield et al. 2006; Li 2016; Stuart et al. 2011). There are numerous studies (Aladejana et al. 2020; Cullet et al. 2017; Cuthbert et al. 2019; Earman and Dettinger 2011; Essefi et al. 2013; Green 2016; Hamed et al. 2018; Hanson et al. 2012; Herrera-Pantoja et al. 2012; Holman 2006; Khalaj et al. 2019; Kurylyk et al. 2014; Li 2016; Malakar et al. 2021; Manning et al. 2013; Mas-Pla and Menció 2019; McGill et al. 2019; Morsy et al. 2017; Moseki 2017; Mukherjee 2018; Panwar and Chakrapani 2013; Sanderson and Curtis 2016; Taylor et al. 2013a; Zaveri et al. 2016; Haque et al. 2020; Khan et al. 2020) available in the literature that can be referred to understand the impacts of climate on groundwater system in general or on particular aspects of groundwater (e.g., quality, recharge, the role of anthropogenic activities, complex interactions, groundwater-dependent ecosystems, hydrocarbon mitigation, sea-level rise, seawater intrusion, groundwater management, etc.).

As the usage and depletion of groundwater are dominated by irrigation, climate change in the future may have significant impacts on groundwater through concomitant irrigation-water demands. Although high uncertainties are associated with the global and regional climate models regarding effects of climate change on rainfall patterns (Bates et al. 2008), it is evident that the hydrological cycle is intensified by climate change, causing an increased number of meteorological extremes (Allan and Soden 2008; Field et al. 2012). An increase in intensity and frequency of heavy rainfall events interspersed with severe and prolonged droughts may induce changes in recharge and discharge of groundwater systems along with irrigation demands. Döll (2002) carried out a global assessment of climate change impacts on irrigation demands and projected increased irrigation water requirements by 2070 for two-thirds of the existing (end of twentieth century)irrigated area.

India is the largest groundwater user in the world, with an annual withdrawal of 230 km^3 for irrigation (Mishra et al. 2018; Sahoo et al. 2021). This is due to a huge population, the majority of which has agriculture as the primary occupation. The lack of adequate irrigation facilities, significant spatiotemporal variation in precipitation and surface water availability, and unsustainable water-use practices have led to excessive dependency on groundwater. Due to the rapid growth of population, urbanization, industrialization, and climate change impacts on water resources, the water demands are expected to rise in the future. Jain (2011) assessed the estimates of water requirements for current and future scenarios over India. The annual water requirements in different sectors over India during the current (2010), near-future (2025), and mid-twenty-first century (2050) for low and high population growth scenarios are presented in Table 1. India is likely to face the problems of water scarcities due to its uncontrolled rise in population and severe consequences of climate change. There is a significant increase in estimated water demands in the mid-twenty-first century as compared to that of 2010, specifically for high-population growth conditions.

On the basis of hydrogeological characteristics, India is classified into 42 major aquifers under 14 principal aquifer systems. The Alluvium is the largest aquifer system covering over 30% of the country's area, followed by Basalt (16.15%), Banded Gneissic Complex (15.09%), Sandstone (8.21%), Shale (7.11%), Gneiss (5.01%), Schist (4.44%), Granite (3.18%), Charnockite (2.41%), Limestone (1.98%), Quartzite (1.48%), Laterite (1.29%), Khondalite (1.04%), and Intrusive (0.63%) systems. The distribution of the principal aquifer systems over India is presented in Fig. 2. The Alluvium aquifers cover a major portion of the states/union territories, viz. Assam, Bihar, Chandigarh, Delhi, Haryana, Puducherry, Punjab, Rajasthan, Uttar Pradesh and West Bengal. As per the geological time scale, the Alluvium and Laterite belong to the Quaternary age, whereas the aquifer systems, viz. Banded Gneissic Complex, Charnockite, and Khondalite belong to Archean (or Azoic) Eon. The major aquifers under the Gneiss and Schist systems are from Archean to Proterozoic geological ages, whereas the aquifers under Sandstone, Shale, Granite and Intrusive systems are from Proterozoic to Cenozoic ages, and the Quartzite aquifers are from Archean to Cenozoic ages. The Basic and Ultrabasic rock aquifers (Basalt system) belong to the Mesozoic to Cenozoic era. The major aquifers under the Limestone system have a geological age from Archean Eon to the Quaternary period. Regarding the aquifer characteristics, the thickness of the aquifer or weathered zone can be up to 700 m for Alluvium, whereas it is up to 600 m and 451 m for Sandstone and Limestone aquifer systems, respectively. On the contrary, the thickness of aquifers ranges from 6 to 13 m, 3–25 m, and 5–20 m for Intrusive, Gneiss and Khondalite systems, respectively. The aquifers under Alluvium and Laterite systems have a very high yield, i.e., up to 6500 m^3/day, while the Intrusive aquifers have the lowest yield. The details of the principal aquifer systems and the major aquifers can be referred from CGWB (2012). Even the groundwater recharge mechanisms are significantly affected by the geological characteristics. Groundwater recharge is driven by low-intensity precipitation in the northwestern and northcentral Indian regions, which are dominated by alluvial aquifers. On the other hand, groundwater recharge is primarily driven by high-intensity and total precipitation in South India, which is dominated by hard-rock aquifers (Asoka et al. 2018).

The groundwater potential depends on the geological formations. The hydrogeological map of India depicts unconsolidated, consolidated/semi-consolidated formations, and hilly areas (Fig. 3). The unconsolidated formations are typically the Alluvial aquifers covering the Indo-Gangetic and Brahmaputra plains, parts of deserted western India (Rajasthan and Gujarat), and the coastal regions. In the deserted areas, groundwater is available at great depths and is often associated with salinity hazards; and the recharge

Table 1 Annual water requirement (in km^3) for different uses in 2010, 2025, and 2050 in India for low and high population growth scenarios (Jain 2011; Panwar and Chakrapani 2013)

Year	2010		2025		2050	
Uses	Low	High	Low	High	Low	High
Irrigation	543	557	561	611	628	807
Domestic	42	43	55	62	90	111
Industry	37	37	67	67	81	81
Power	18	19	31	33	63	70
Inland navigation	7	7	10	10	15	15
Environment- ecology	5	5	10	10	20	20
Evaporation loss	42	42	50	50	76	76
Total	694	710	784	843	973	1180

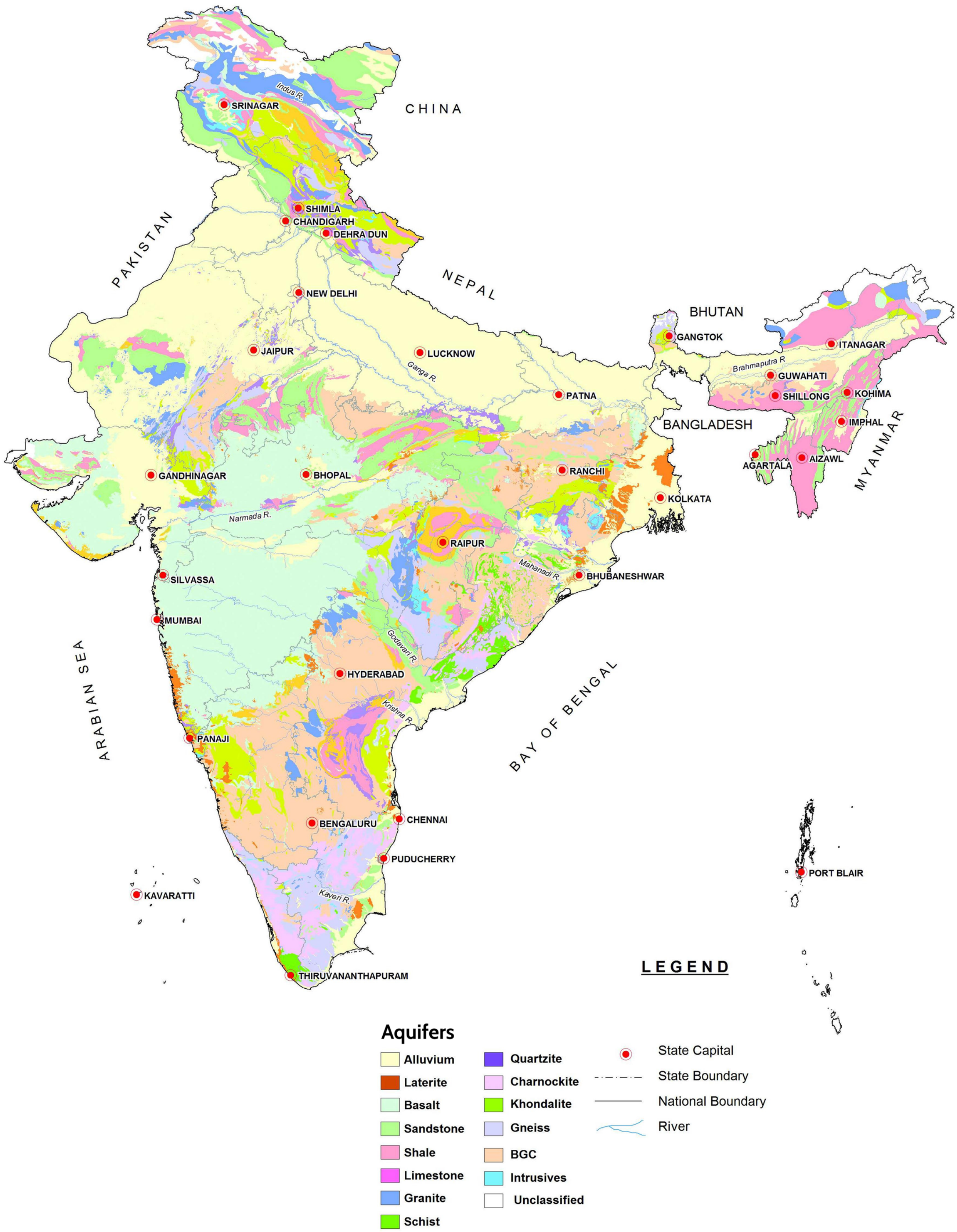

Fig. 2 Principal aquifers of India (*Source* http://cgwb.gov.in/)

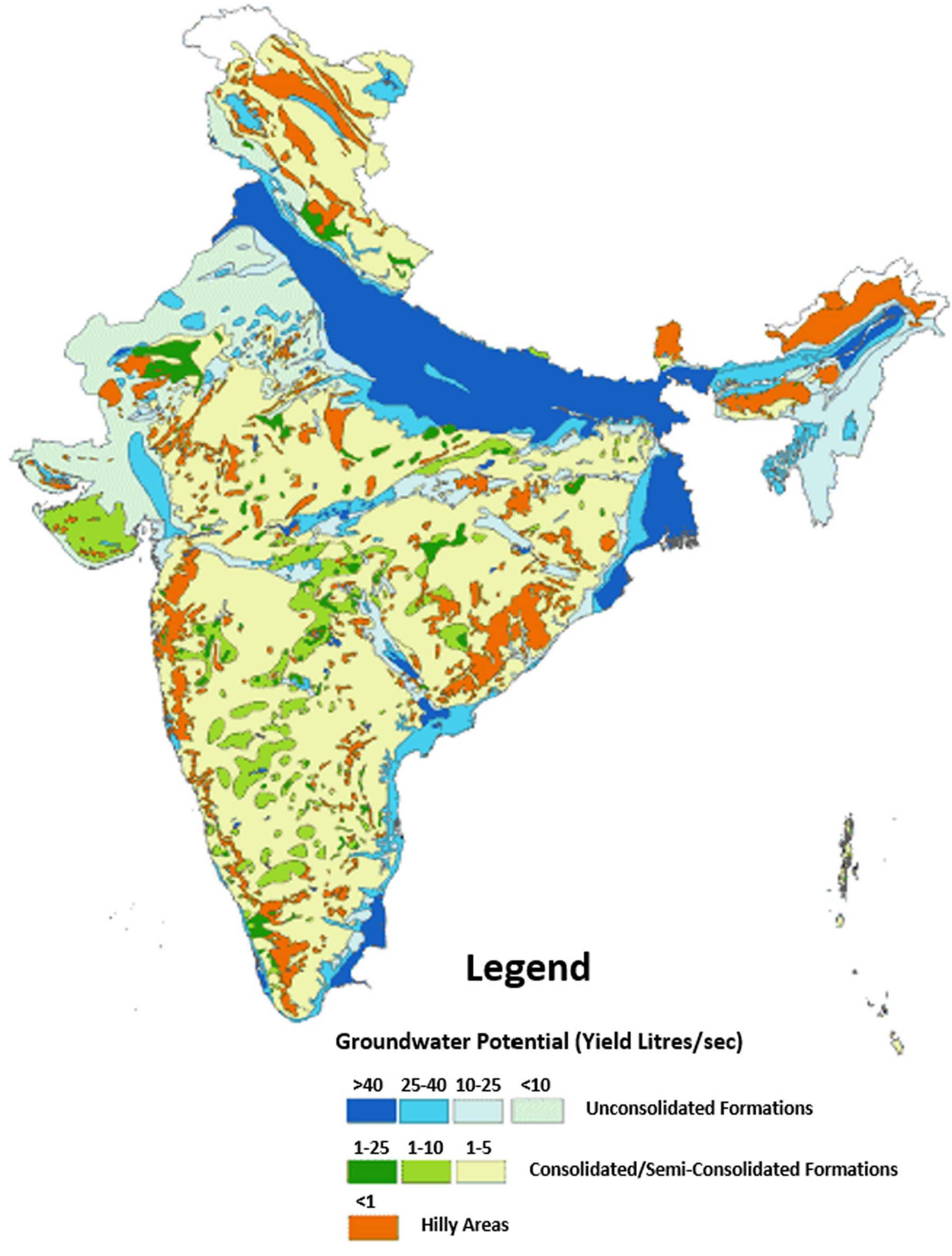

Fig. 3 Hydrogeological map of India (*Source* http://cgwb.gov.in/)

is negligible due to scanty rainfall. There are reasonably extensive aquifers in the coastal regions; however, they suffer from a risk of seawater intrusion. The Indo-Gangetic and Brahmaputra plains receive high rainfall, thereby ensuring groundwater recharge. These regions have huge reserves down to 600 m depth, which supports developmental activities through deep tubewells. The consolidated or semi-consolidated formations (basalts, sedimentaries and crystalline rocks) covering the Peninsular India are associated with varying yields and depths to the groundwater table. The secondary porosity (i.e., the openings in rocks created after their formations due to fracturing, weathering, etc.) govern the groundwater availability (CGWB 2018). The hilly areas typically have low groundwater potential mainly because of the high slopes leading to quick runoff, which results in a low storage capacity. The spatiotemporal variability of groundwater storage in India and long-term groundwater recharge rates by in situ observations are well documented in the literature (Bhanja et al. 2017b, 2019b; Mukherjee et al. 2015; Khan et al. 2020). Moreover, A study by Saha et al. (2020) provides recent scientific perspectives on Indian hydrogeology.

The depth to groundwater level (DGWL) over the Indian region in four seasons, i.e., summer (May 2019), monsoon (August 2019), post-monsoon (November 2019), and winter (January 2020) during the year 2019–20, is presented in Fig. 4. It is evident that the DGWL is highest in the summer season and lowest in the monsoon season. As DGWL is measured beneath the ground from the surface, a higher DGWL implies a lower water level. Hence, the groundwater level is highest in the monsoon season, followed by post-monsoon and winter seasons, and the lowest in the summer season. The results are obvious as most of the Indian regions receive a majority of annual rainfall during the monsoon season, which directly recharges the groundwater. In the subsequent seasons, i.e., post-monsoon, winter, and summer, people mostly depend on groundwater and available surface water due to the unavailability of rainfall. Since the surface waterbodies dry up or reach the lowest points during the summer season, groundwater extraction increases significantly. Therefore, groundwater level decreases from monsoon towards summer season. Regarding spatial variation, the pattern is quite similar in all the seasons, excluding the south Indian region. The DGWL is very high over Punjab, Haryana and Rajasthan. This is due to the fact that these regions fall under semi-arid to arid climates, where rainfall is scanty and fluctuating. Therefore, agriculture in these regions is primarily dependent on groundwater systems. Similarly, the semi-arid regions of Maharashtra also show high DGWL. The regions, viz. Western Ghats, northeastern states and coastal regions, have water tables at shallow depths, as these regions receive higher amounts of rainfall. Interestingly, the south Indian region shows a contrasting spatiotemporal pattern with respect to the rest of India. This is due to the fact that some of these regions receive higher rainfall in November due to the retreat of the monsoon.

Gravity recovery and climate experiment (GRACE): a new way for groundwater study

With the advancement of technology, remote sensing and geographic information system (GIS) has become instrumental in different engineering applications. In relation to groundwater, remote sensing and GIS applications include groundwater potential mapping, site selection for recharge structures, monitoring water level changes, mapping fault segments and ground deformations, groundwater storage estimation, etc. These investigations consume a lot of time, resources, and effort if carried out on the field. In last two decades, the use of Gravity Recovery and Climate Experiment (GRACE) in groundwater storage estimation has gained remarkable attention. The GRACE mission was launched in March 2002, where twin satellites took detailed measurements of Earth's gravity field anomalies by relating it to the distance between them. These measurements were instrumental in improving the estimations of terrestrial water storage (TWS) changes, especially in conjunction with other models and data (Li et al. 2019). The GRACE mission ended in October 2017. Nevertheless, in May 2018, Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) satellites were launched to continue the mission and have been operational since then.

The information provided by GRACE and GRACE-FO has been used in different sectors over the Indian region. Bhanja et al. (2016) validated the GRACE-based groundwater storage (GWS) anomalies over India using in situ GWL measurements from over 15,000 observation wells. For most of the regions, the GRACE-based estimates and the observed data possessed good agreement, justifying the utility of GRACE satellites. Soni and Syed (2015) diagnosed the TWS variations from GRACE satellites and linked it to the role of hydrologic fluxes over four major river basins (Mahanadi, Krishna, Godavari and Ganga) of India. TWS had a declining trend over the Ganga basin; however, it showed an increasing trend over the remaining three basins. Bhanja et al. (2020) carried out a similar study over all 22 of India's major river basins to detect GWS changes using GRACE-based estimates and in situ data. Increasing or indeterminate trends of GWS were observed over most of the basins, which were well correlated with the precipitation changes. However, GWS had undergone a significant decline over Ganges and Brahmaputra basins, which is a serious concern for agriculture over North India. Vissa et al. (2019) investigated the role of El Niño-Southern Oscillation (ENSO) in groundwater changes over India using GRACE data. The interannual variations in rainfall were responsible for the interannual GWS changes. ENSO was found to be a major controller of GWS changes, i.e., El Niño and La Niña periods were associated with the decline and

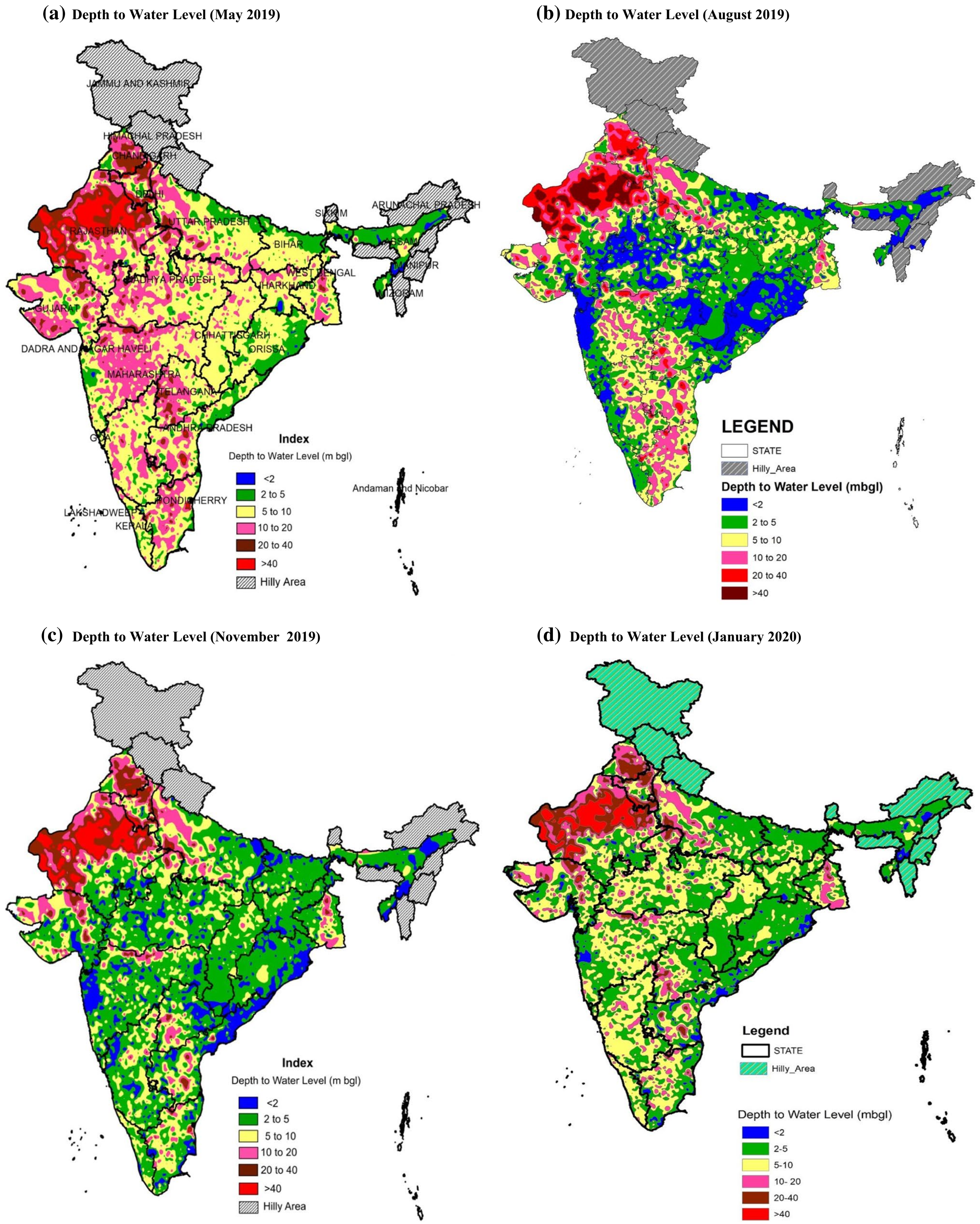

Fig. 4 Depth to groundwater level over Indian region during **a** Pre-monsoon, **b** Monsoon, **c** Post-monsoon, and **d** Winter seasons (*Source* CGWB 2020a)

recovery of GWS, respectively. Long et al. (2016) utilized GRACE data to analyze groundwater depletion in northwestern India. The aquifers of the region showed a severe decline in GWS, posing a threat to agricultural output and groundwater sustainability. The depletion of groundwater in some parts of India and its repercussions have also been discussed in several studies (Bhanja and Mukherjee 2019; Dalin et al. 2017; Girotto et al. 2017; Goldin 2016; Panda and Wahr 2016; Rodell et al. 2009; Tiwari et al. 2009; Sarkar et al., 2020; Singh et al. 2017 and 2021; Karunakalage et al. 2021a,b). Asoka et al. (2017) assessed the relative contribution of monsoon precipitation and pumping to GWS changes in India. Groundwater pumping for irrigation was highly influential over the northwestern portions, whereas the precipitation variability was the governing factor over southern and north-central India. A decreasing precipitation over northern India induced by Indian Ocean warming was responsible for declining GWS. Singh et al. (2019a) utilized GRACE data for monitoring groundwater fluctuations over India during southwest and northeast monsoon seasons. The results revealed an enhancement of 6.45 cm over Peninsular India during the northeast monsoon and 13 cm over entire India during the southwest monsoon season. The study recommended applying drip irrigation techniques over the country, especially in northern and northwestern India, to obtain better yield with less water available. Bhanja et al. (2017a) assessed the impacts of implementing the groundwater policy changes on aquifer replenishment in parts of India using GRACE data. The aquifers in southern and western India were found to be rejuvenated due to a paradigm shift in groundwater withdrawal and management policies. Using continuous GRACE observations, Saji et al. (2020) aimed to understand the ground deformation in response to hydrological mass variations of North India and the Himalayas. The results revealed a subsidence of Indo-Gangetic Plain and sub-Himalaya regions, which can be attributed to natural geological (tectonic and nontectonic) forcings, excessive groundwater withdrawals, and other human activities. Bhanja et al. (2019a) explored the relation of Normalized Difference Vegetation Index (NDVI) with GWS derived from GRACE satellites over the Indian land region, and they were well correlated in natural vegetation-covered areas. Sinha et al. (2017) proposed a water storage deficit index (WSDI) based on the GRACE-derived TWS variations to quantify drought characteristics over India. The study substantiated the potential of WSDI in characterizing droughts over large spatial scales. Nair and Indu (2020) investigated the impact of severe meteorological droughts on GWS in India. The depletion of groundwater was found to exacerbate after severe droughts, mostly due to increased dependency of the populace on groundwater resources during surface water-deficit conditions induced by droughts. Kumar et al. (2021b) suggested using GRACE-based TWS estimates for real-time drought monitoring major river basins in South India. Similarly, Gupta and Dhanya (2020) evaluated the potential of GRACE in assessing the flood potential of Peninsular basins of India and suggested incorporating TWS along with precipitation data in hydrological modeling to assess flood events. Xie et al. (2020) employed GRACE estimates to improve the hydrological model representation of anthropogenic water use impacts. The integration of groundwater irrigation into hydrological simulations was found to be useful.

Overall, GRACE has contributed to enhancing the existing knowledge of hydroclimatic processes to improve water resources management in India. It can also be utilized effectively in the characterization of extremes. The limitations of using GRACE estimates over the Indian region have been documented in a few studies (Long et al. 2016; Girotto et al. 2017; Sun et al. 2019; Xie et al. 2020). Nevertheless, enhancing the spatiotemporal resolution of GRACE data and coupling it with additional hydroclimatic datasets from satellites missions (e.g., SWOT, SMAP, GPM) may be instrumental in reducing the uncertainties (Soni and Syed 2015). Moreover, including the availability of in situ measurements, the contributions from surface water bodies and irrigation into the numerical/hydrological models can further improve the GWS or TWS estimates.

Groundwater and sea-level rise

The coastal lands are typically associated with large concentrations of human settlements. Even a number of large cities in the world are situated near the shorelines. Small and Nicholls (2003) carried out a global analysis of the population in coastal regions. The near-coastal population (characterized as within 100 m of sea level and 100 km of shorelines) was estimated to be 1.2 billion. The average density in such regions is thrice as compared to the average global density. Since anthropogenic activities have major impacts on the natural processes, the vulnerability and exposure to hazards are always high in coastal regions. Coastal aquifers provide water to above one billion population residing in coastal areas. They form the interface between the oceanic and terrestrial hydrological systems (Taylor et al. 2013a). During 1950–2000, the global sea -level rise (SLR) is reported to be 1.8 mm/year (Solomon et al. 2007). A higher rate of SLR may make fresh–saline-water interfaces to move inland (Taylor et al. 2013a), which may cause saline water-intrusion (SWI). The SWI into coastal aquifers is dependent on various factors, viz. groundwater abstraction, recharge, coastal topography, etc. (Dhal and Swain 2022; Ferguson and Gleeson 2012; Oude Essink et al. 2010). Ferguson and Gleeson (2012) suggested that the effect of groundwater abstraction on SWI is significantly higher compared to that of SLR. The effects of SWI are mostly reported in regions associated with high population densities causing uncontrolled groundwater abstraction, e.g., Gaza, Jakarta, Bangkok etc. (Taniguchi 2011; Yakirevich et al. 1998). In Asian mega-deltas, the coastal aquifers are expected to be sensitive to SLR due to very low hydraulic gradients; however, they are projected to face more severe consequences from storm surge-induced saltwater inundation than SLR (Ferguson and Gleeson 2012).

The role of groundwater depletion in SLR is not very well specified. Due to the uncertainty associated with estimations of groundwater depletion, no clear description of their contribution to sea-level variation was there in the *Intergovernmental Panel on Climate Change* (IPCC) fourth assessment report (Solomon et al. 2007). However, some recent studies have evaluated the role of groundwater depletion in SLR (Konikow 2011; Pokhrel et al. 2012; Wada et al. 2010, 2012). The continent-wise estimates of groundwater depletion and SLR during 2001–08 (Konikow 2011; Taylor et al. 2013a) are presented in Table 2. The global groundwater depletion is estimated to be 145 ± 39 km^3/year, which is principally contributed by the Asian continent (111 ± 30 km^3/year). The global SLR is estimated to be 0.40 ± 0.11 mm/year, whereas the Asian SLR is estimated to be 0.31 ± 0.08 mm/year. For both groundwater depletion and SLR, the worst affected continent is Asia, followed by North America, Africa, Europe, South America, and Australia. The aggravated condition in Asia is mainly due to its high population and increasing per capita water scarcity. However, the estimates provided in Table 2 are modelled estimates and not based on direct observations. The lack of ground-based observations limits the understanding of localized changes in groundwater storage. Apart from all the aforementioned issues of SLR, the evident impacts of climate change on SLR and the aggravating SWI may also cause migration of people from the coastal areas (McLeman 2019; Wrathall et al. 2019). It is a serious matter for India due to its highly concentrated population in coastal areas. India is surrounded by marine water bodies, i.e., the Arabian Sea in the southwest, the Bay of Bengal in the southeast, and the Indian Ocean in the southern edge. Several studies have highlighted the vulnerability of Indian coasts to SLR (Dwarakish et al. 2009; Rao et al. 2008; Shetye et al. 1990; Swapna et al. 2020; Unnikrishnan et al. 2015). Han et al. (2010) predicted increased environmental stress on some coasts and islands in the Indian Ocean under a warming climate. Swapna et al. (2020) predicted frequent occurrences of extreme sea-level events over the Indian coasts associated with a rise in the mean sea level and climatic extremes. Prusty and Farooq (2020) presented an overview of the problem of seawater intrusion in the coastal aquifers of India. These studies emphasize that coastal managers must devise proper planning and management strategies to protect the environmental and socio-economic security of coastal communities.

Table 2 Groundwater depletion and SLR estimates over different continents during 2001–08 (Konikow 2011; Taylor et al. 2013a)

Continent	Groundwater depletion (km^3/yr)	Sea-level rise (mm/yr)
Asia	111 ± 30	0.31 ± 0.08
Africa	5.5 ± 1.5	0.015 ± 0.004
North America	26 ± 7	0.07 ± 0.02
South America	0.9 ± 0.5	0.002 ± 0.001
Australia	0.4 ± 0.2	0.001 ± 0.0005
Europe	1.3 ± 0.7	0.004 ± 0.002
Global	145 ± 39	0.40 ± 0.11

Groundwater quality (GWQ) in India

The rapidly depleting water resources as a cause of anthropogenic activities, coupled with the uncontrolled population growth, has resulted in a sharp decline in the per capita water availability over the Indian region. In such conditions, the quality of the available water resources becomes vital. Water is regarded to be polluted when its quality or composition alters by either natural or anthropogenic activities and becomes less suitable for domestic, agricultural, or industrial applications (Adimalla and Venkatayogi 2018; Adimalla et al. 2019a, 2019b; He et al. 2020; Sudhakar and Narsimha 2013; Swain et al. 2022c; Xu et al. 2019). Further, consumption of water with degraded quality may lead to several dangerous consequences (Adimalla and Qian 2020 and 2021; Adimalla et al. 2021; Bahita et al. 2021a, b; Yahaya et al., 2012; Zhang et al. 2019 and 2020a, b). Many water bodies of India have become polluted due to the discharge of domestic sewage, municipal waste drains, urban agricultural waste, and large-scale industrial effluents (Kaur and Kaur 2015). Nearly 70% of rivers and streams in India contain polluted waters (Goel 2006; Jain et al. 2007; Bahita 2019), which adds to the stresses on groundwater quality.

India is the largest user of groundwater in the world, and a vast majority of the groundwater usage goes for irrigation purposes. Moreover, almost half of the urban population and four-fifths of the rural population use groundwater for domestic purposes without any treatment. Regarding groundwater quality in India, there is a significant spatiotemporal variation due to groundwater availability, underlying strata, the extent of usage, and several other factors (Nishy and Saroja 2018). Therefore, regular assessment of water quality carries remarkable importance, which is reflected in the increasing number of water quality evaluation studies over the Indian region in recent days. The evaluation of water quality is usually carried out by measuring the concentrations of different parameters and checking it with their prescribed limits for specific uses, i.e., the permissible limits of the parameters for irrigation purposes are different from that of domestic purposes. These water quality parameters can be divided into three broad categories, (a) physicochemical, (b) heavy metal, and (c) biological (EPA 2001).

The parameters relevant to physical and chemical quality aspects of water are together referred to as physicochemical parameters. The physical parameters mainly include color, odor, temperature, and turbidity, whereas the chemical parameters mainly include pH, electrical conductivity (EC), total dissolved solids (TDS), Calcium, Magnesium, Nitrates, Chlorides, Fluorides, Phosphates, Sulphates, Sodium, Potassium, Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and Dissolved Oxygen (DO) (Omer 2019). Some of these physicochemical parameters are associated with serious health repercussions and are regularly monitored by the Central Ground Water Board (CGWB), Government of India. The current conditions of physicochemical water quality parameters in groundwater over the Indian region are presented in Fig. 5, which is referred from CGWB (2018). It is noticeable that EC values are significantly higher (> 3000 µs/cm) over Rajasthan, Gujarat, Haryana, and some portions of South India (Fig. 5a). EC is used to diagnose the concentration of soluble salts and thus, is an effective tool to detect salinity problems. A high EC is considered unsuitable for plants (Semwal and Alkolkar 2011). Figure 5b presents the groundwater observation points in India with a high nitrate concentration (> 45 mg/l) as identified by CGWB (2018). A major portion of the country is affected by high nitrate concentrations. This can be attributed mainly to anthropogenic causes, viz. intensive agriculture with heavy use of nitrogenous fertilizers, irrigation by sewage effluents, unsewered sanitation in populated regions, etc. The deposits of nitrate and soil erosion are also amongst the main natural contributors of nitrates in groundwater (Zhang et al. 2021a, b). Nitrate is an essential nutrient for plants and animals, including human beings; however, regular consumption of water with high nitrate concentrations can cause severe health consequences, e.g., blue-baby syndrome, secretive functional disorders of the intestinal mucosa, vascular dementia, Alzheimer disease, and gastrointestinal cancer (Suthar et al. 2009). The Chloride concentrations are very high (above 1000 mg/l) over Gujarat and Rajasthan, and high (above 250 mg/l) in some parts of northwestern as well as southern India and the state of West Bengal (Fig. 5c). The primary reason for high Chlorides in groundwater may be the underlying aquifer structure. The aquifer's predominant ions are found in higher concentrations in the groundwater. Industrial wastes, fertilizers, septic tank effluents are also some of the major anthropogenic reasons. Since West Bengal and the southern Indian states come under coastal regions, seawater intrusion may be a prominent reason for the increase of Chlorides and other salts in groundwater. The high concentrations of Fluoride (> 1.5 mg/l) are mostly found in Karnataka, Telangana, Andhra Pradesh, Gujarat, Rajasthan, Punjab, Haryana, Odisha, West Bengal, and Jharkhand states (Fig. 5d). The geochemistry of high Fluoride in groundwater is often linked with high sodium and bicarbonate concentrations, low calcium concentrations, and neutral to alkaline pH (Adimalla and Li 2019; Adimalla et al. 2018b; Narsimha and Sudarshan 2017a, b). The weathering of Fluoride-rich rocks and volcanic ash are the principal natural sources of Fluorides in groundwater (Sakram and Adimalla 2018; Sakram et al. 2019). The anthropogenic activities include industrial activities, fertilizers, fly ash from the combustion of fossil fuels etc. Intake of water with excessive Fluoride may cause dental and skeletal fluorosis, deformities in red blood cells, low hemoglobin levels, male sterility, neurological manifestations, reduced immunity, etc. Generally, the concentrations of Fluoride are found to be increasing with an increase in depth of the water table from the ground level. Since India is the world's largest groundwater user and groundwater extraction has significantly increased in recent years due to high water demands, increased Fluoride concentration may be a serious concern in the future.

Heavy metals are also important parameters for water quality. The heavy metals include Arsenic (As), Cadmium (Cd), Chromium (Cr), Cobalt (Co), Copper (Cu), Iron (Fe), Lead (Pb), Manganese (Mn), Mercury (Hg), Nickel (Ni), Uranium (U), and Zinc (Zn). They are often regarded as trace metals too. Although 'heavy' and 'trace' may seem contrasting, they are based on different aspects. The 'heavy' term is relevant to the specific gravity of the metals. The metals with a density greater than 5 g/cm3 in their elemental form are called heavy metals (Tomar 1999; Bahita 2019). On the other hand, 'trace' indicates that they are present in very tiny concentrations (generally in parts per million). Hence, the heavy metals have small units of presence (or in trace quantities) in a water sample. Some of these metals act as essential nutrients for the human body. However, these metals possess toxicity in higher than desirable concentrations, which may be imparted to water (Gambrell 1994; Bahita 2019). The occurrence of these heavy metals in groundwater may be due to natural processes or as effects of anthropogenic activities.

Similar to physicochemical parameters, heavy metals also possess remarkable spatial variation across the country. CGWB regularly monitors the concentrations of some of these crucial heavy metals in groundwater. However, only the concentrations of Arsenic, Iron, and Uranium all

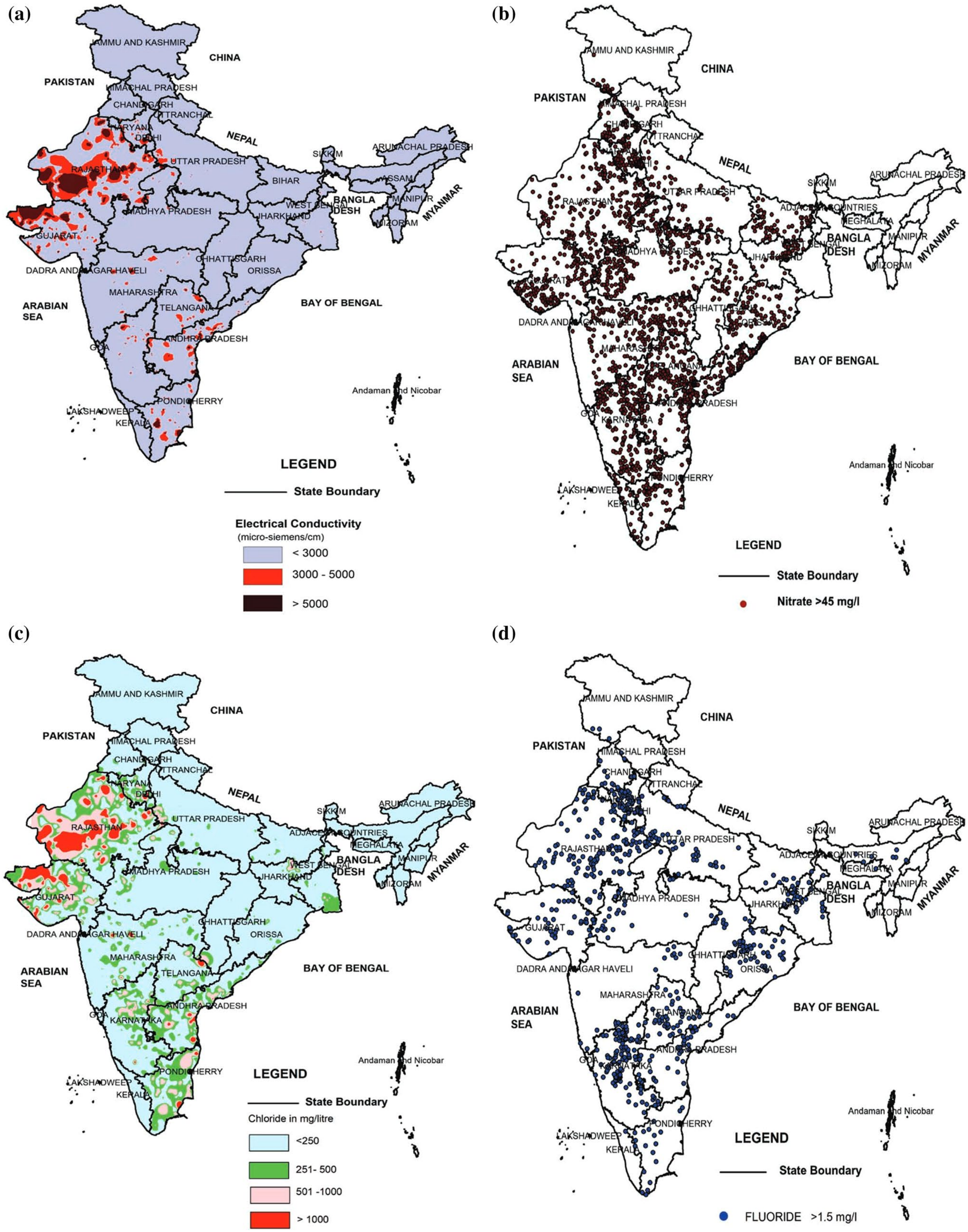

Fig. 5 The water quality condition of India in terms of physicochemical parameters, **a** Electrical conductivity, **b** Nitrate, **c** Chloride, and **d** Fluoride (*Source* CGWB 2018)

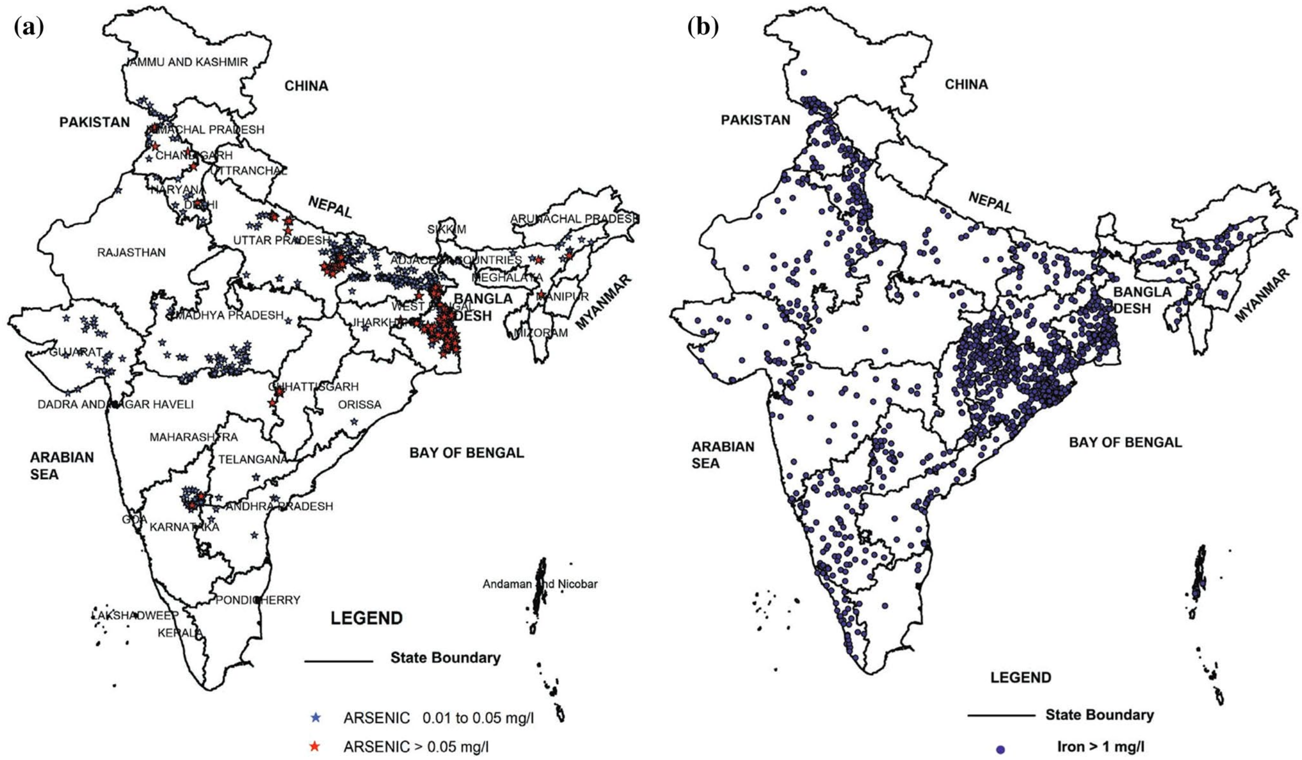

Fig. 6 The water quality condition of India in terms of heavy metal parameters, **a** Arsenic, **b** Iron (*Source* CGWB 2018)

over India are available in their recent reports, i.e., CGWB (2018 and 2020b). World Health Organization (WHO) and the Bureau of Indian Standards (BIS) recommend 0.01 mg/l to be the permissible limit of Arsenic in water and 0.05 mg/l in the absence of an alternative source (Bahita et al. 2021a). Figure 6a presents the locations of groundwater observation points with very high (> 0.05 mg/l) and high (0.01 to 0.05 mg/l) Arsenic concentrations. The high Arsenic in groundwater can be mostly observed in West Bengal, Bihar, Uttar Pradesh, Assam, Punjab, Haryana, Madhya Pradesh, Gujarat, and Karnataka. Arsenic is observed mostly in the aquifers less than 100 m in depth. Groundwater in deeper aquifers is free from Arsenic occurrence (Shamsudduha et al. 2019). In 1980, West Bengal was the first state of India to report Arsenic occurrence in groundwater (Mukherjee and Fryar 2008; Mukherjee et al. 2011). At present, over eighty blocks in eight districts of the state have been reported to have a very high Arsenic concentration, and thus, the groundwater is not fit for domestic use (CGWB 2018). High Arsenic content in water is very harmful to plants and animals. The inorganic Arsenic may cause serious health consequences, e.g., cancer, peripheral neuropathy, cardiovascular diseases, gastrointestinal disorder, and diabetes. Dissolution of minerals and discharge of untreated industrial effluents are the primary sources of Arsenic in water and the atmosphere (WHO 2004). Figure 6b shows the observation points with an iron concentration beyond the permissible limit of 1 mg/l. While a majority of the Indian region is observed to be affected by excessive iron in groundwater, the number of such observations is higher in Odisha, Chhattisgarh, West Bengal, Jharkhand, Bihar, Assam, Punjab, Haryana, Kerala, and Karnataka. Generally, high iron contents in water are not linked to severe health consequences; however, they have serious aesthetic issues (e.g., staining problems, bad taste). The anthropogenic causes of high iron concentration in groundwater are acid-mine drainage, landfill leachate, discharge of industrial wastes, etc. Iron being the most abundant heavy metal and the fourth-most abundant element in the earth's crust, its natural occurrence in groundwater is due to geological formations and weathering of rocks and soils.

Uranium is a radioactive element with a density of 19 gm/cm^3, which occurs naturally in trace concentrations. It is mainly present in granite rocks and soils. The human ingestion of natural Uranium is predominantly by drinking water. According to the Atomic Energy Regulatory Board (AERB) of India, no deleterious radiological health effects of Uranium can be expected below a concentration of 60 ppb (or μg/L). However, as per WHO, consumption of water with Uranium contents beyond 30 ppb may have harmful chemical effects on human health, if not radiological effects. As high-Uranium water leads to serious renal (kidney) damages, CGWB has actively monitored its concentration in the

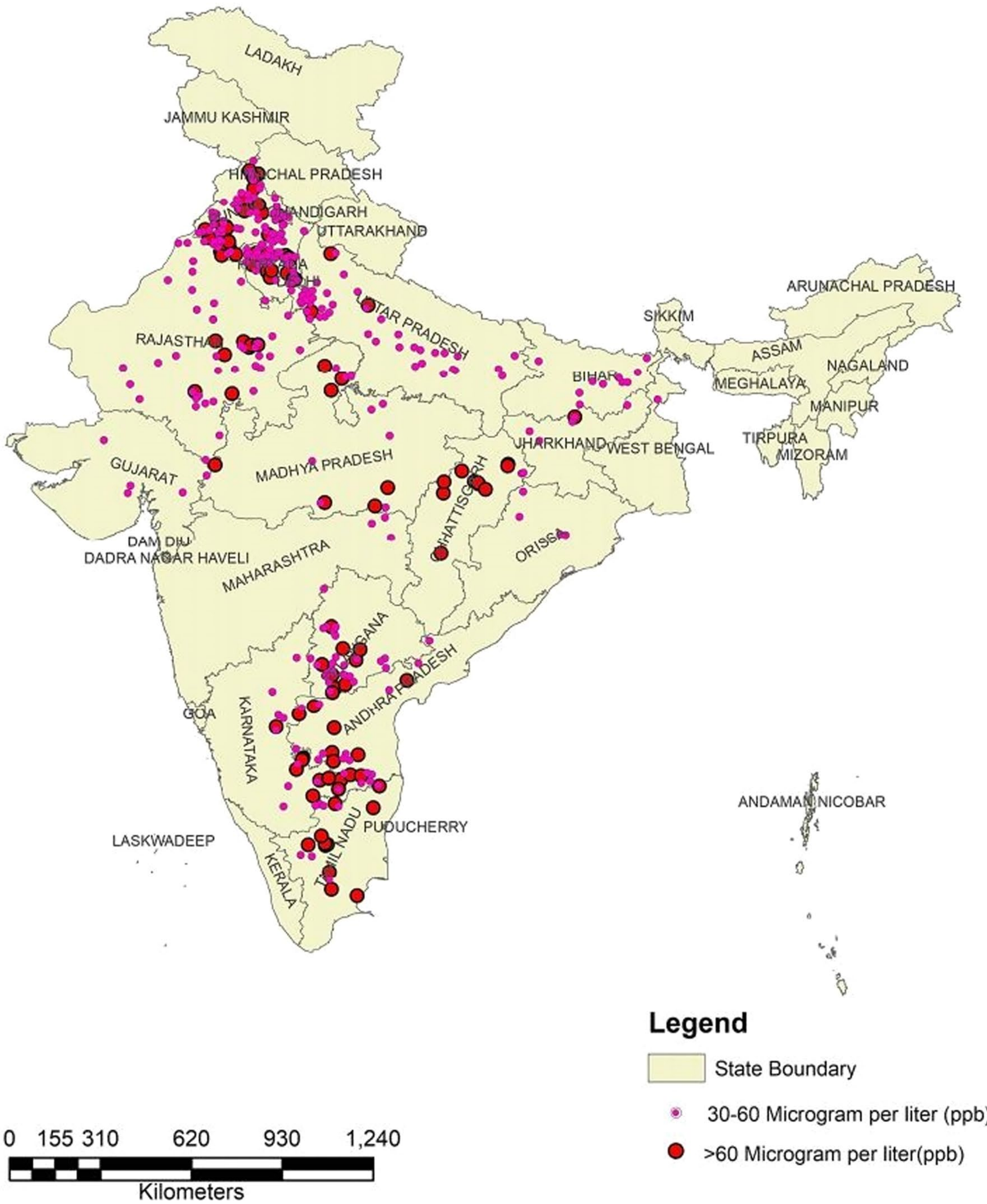

Fig. 7 Location of high Uranium concentrations in shallow aquifers in India (*Source* CGWB 2020b)

groundwater of shallow aquifers all over India. An analysis of 14,377 samples collected during 2019–20 revealed a significant variation of Uranium concentration in groundwater, ranging from 0 to 2876 ppb. The locations of very high (> 60 ppb) and high (30 to 60 ppb) concentrations in shallow aquifers in India are presented in Fig. 7. Detailed information on the total number of samples analyzed and the number of samples beyond the permissible limit of WHO and AERB in different states/ union territories can be referred from Fig. 8. Overall, 151 districts in 18 states are found to be affected by high Uranium in groundwater. The states with at least 4% of the samples beyond WHO limits are Uttar Pradesh (4.4%), Andhra Pradesh (4.9%), Rajasthan (7.2%), Telangana (10.1%), Delhi (11.7%), Haryana (19.6%) and Punjab (24.2%). Further, the states with above 0.5% of the samples beyond AERB limits are Madhya Pradesh (0.6%),

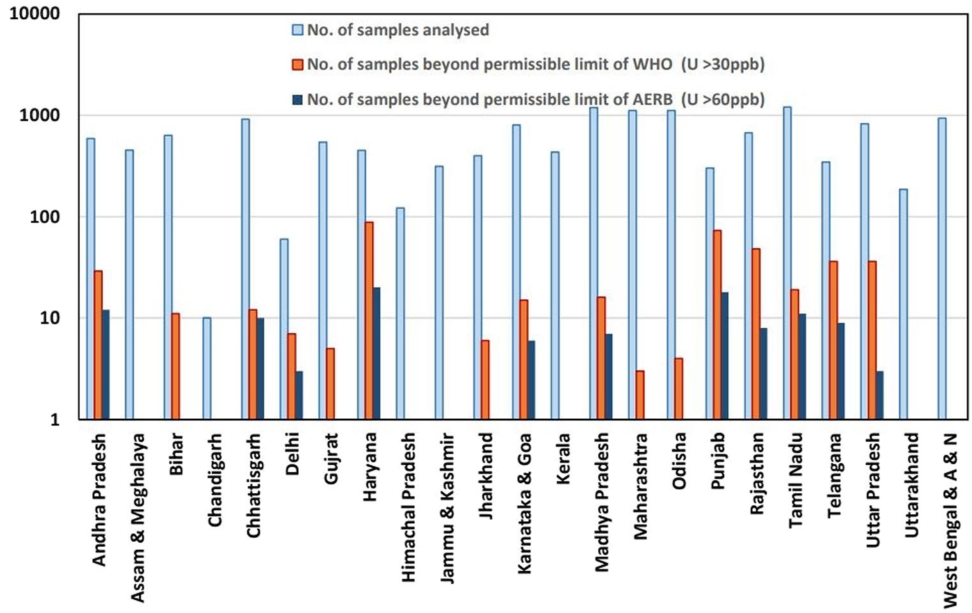

Fig. 8 Status of Uranium in groundwater of different States/Union Territories in India (*Source* CGWB 2020b)

Karnataka (0.7%), Tamil Nadu (0.9%), Chhattisgarh (1.1%), Andhra Pradesh (2%), Rajasthan (1.2%), Haryana (4.4%), Delhi (5%) and Punjab (6%). The remediation of Uranium contamination is achieved by several technologies, viz. reverse osmosis (RO) membrane separation, precipitation, evaporation, extraction, coagulation, etc., which makes the groundwater potable. A field study in Punjab found Uranium concentrations of RO treated water to be less than 0.1 μg/L (CGWB 2020b).

The biological water quality intends to represent the presence/absence of water-borne pathogens or microbiological organisms, e.g., viruses, bacteria, parasites, protozoa, and algae. These pathogens are responsible for several water-borne diseases, viz. cholera, hepatitis, polio, dysentery, diarrhea, typhoid, schistosomiasis, etc. (Pandey et al. 2014). The intestinal bacteria (pathogenic) are discharged by human beings and animals in the form of urine and faeces. Some of these bacteria are *Vibrio cholera*, *Salmonella*, *Yersinea enterocolitica*, and *Shigella*, which can be present in drinking water if the source of water is contaminated with faeces. In microbial assessments of water quality, *E. coli* (Escherichia coli), which consists of a diverse group of bacteria, is the most commonly used indicator for bacterial pollution. Its presence in water indicates recent faecal contamination, which may be hazardous to health upon consumption. The details of biological parameters of water quality may be referred from literature (Ashbolt et al. 2001; Kumar et al. 2014a; NRC 2004). In general, microbial pollution is associated with surface water bodies. The biological contamination of groundwater can be mostly linked to leakage of septic tanks, untreated disposal of domestic sewage, penetration of surface water carrying animal wastes to groundwater abstraction wells, etc. (Takal and Quaye-Ballard 2018).

Sackaria and Elango (2020) comprehensively reviewed the literature available on organic micropollutants in the groundwater of India. The presence of pesticides, artificial sweeteners, personal care products, per- and poly-fluoroalkyl substances, phthalates, surfactants, pharmaceuticals and endocrine-disrupting compounds were reported in different parts of India. The study also emphasized the need for extensive research on the microbial pollution of groundwater in the Indian region.

Regarding groundwater quality investigations, several studies have been carried out over different parts of India focusing on physicochemical parameters, heavy metals, micropollutants, or the overall contamination status of water. Nishy and Saroja (2018) carried out a scientometric examination of the water quality research in India and concluded a steady growth in the number of water quality assessments. The study also revealed that India ranks seventh and ninth in terms of the number of publications and quality of research output, respectively, relevant to water quality analyses among all the countries. Therefore, it is difficult to summarize the results of all the studies in a single manuscript; however, some of the studies referred by the authors are listed in Table 3. These studies present the major groundwater problems (e.g., hardness, salinity, increased contamination of Arsenic, Nitrate, Fluoride, Uranium, micropollutants) across different parts of India. The methodologies include health risk assessment, drinking/irrigation suitability assessments, and adjudging the overall contamination status of water using multivariate approaches like water quality index (WQI) or its modified forms.

Table 3 Studies for major groundwater quality problems in recent years over India

S. No	Authors	Major GWQ Problems	Index/Methods	State/Regions
1	Machiwal et al. (2011)	Hardness	GWQI	Udaipur District, Rajasthan
2	Kumar et al. (2014b)	Uranium	MEDUSA	Bathinda and Mansa Districts, South Punjab
3	Adimalla (2019)	Nitrate, Fluoride	HRA	Medak region, Western Telangana
4	Adimalla (2020)	Nitrate	DWQI, HRA	Peddavagu region, Central Telangana
5	Aggarwal et al. (2020)	Magnesium Hazard	WQI, FTIR	Alwar, Rajasthan
6	Ahada and Suthar (2017)	Nitrate, Fluoride, Hardness	WQI, SAR, LSI, PI	Malwa region, Punjab
7	Reza and Singh (2009)	COD, Turbidity	Physio-chemical analysis	Angul-Talcher region of Orissa
8	Hundal et al. (2009)	Arsenic	Redox potential, Statistical analysis	Amritsar City, Punjab
9	Aravinthasamy et al. (2020)	Fluoride	Multivariate statistical analysis, HCA, FA	Southern part of the Tamil Nadu
10	Sahoo et al. (2014)	Arsenic, Hardness, Fluoride, TDS	WQI, GIS-based interpolation	Rupnagar district, Punjab
11	Bajwa et al. (2017)	Uranium	HRA, RRA, CTR	South Watern region, Punjab
12	Ghosh et al. (2020)	Arsenic	Spatial interpolation technique	North 24 Parganas, West Bengal
13	Maity et al. (2020)	Arsenic	WQI, HRA, HQ, CDI, HI	Bhojpur, Bihar
14	Marghade et al. (2020)	Nitrate, Fluoride	EWQI, HRA	Godavari basin, Maharashtra
15	Rajkumar et al. (2020)	Heavy metals (Cd, Cr, Fe, Ni and Pb)	HPI, HCI, HEI	Nalagarh valley, Himachal Pradesh
16	Prajapati et al. (2017)	Fluoride	Spatial interpolation technique	Surat district, Gujarat
17	Raju et al. (2012)	Fluoride	Statistical analysis, XRD sampling	Kachnarwa region, Sonbhadra, Uttar Pradesh
18	Rao et al. (2017)	TDS, EC and TH	Statistical analysis, Ion exchange analysis	Western Delta region of the River Godavari, Andhra Pradesh
19	Singh et al. (2019b)	Arsenic, Lead, Chromium	HPI, MI, HRA	Ludhiana Industrial Town, Punjab
20	Kanmani and Gandhimathi (2013)	TDS, Chloride and Lead	Statistical analysis, Contour profiling	Tiruchirappalli District, Tamil Nadu
21	Jha et al. (2020)	TDS, Nitrate, Fluoride, Hardness	FGQI	Tiruchirappalli District, Tamil Nadu
22	Dahiya et al. (2007)	Fluoride, TDS, TH and Sulphate	Fuzzy synthetic evaluation model	Southern region, Haryana
23	Krishan et al. (2021)	Salinity Hazard	Isotopic and Tritium analysis	South-west region, Punjab
24	Ali et al. (2021)	Fluoride	Saturation Index, XRD sampling and statistical analyses	Older Alluvial Plain of Delhi
25	Mukherjee et al. (2018)	Arsenic, Iron and Manganese	Isotopic and Sedimentary analysis	Bhagirathi-Hoogly basin, Murshidabad district, West Bengal
26	Chatterjee et al. (2010)	Arsenic	Statistical Analysis, Arsenic pathway exposure modeling	Ganges–Brahmaputra–Meghna deltaic alluvium, West Bengal
27	Sackaria and Elango (2020)	Organic micropollutants	Literature review	Different parts across India

GWQI ground water quality index, *MEDUSA* make equilibrium diagrams using sophisticated algorithms, *HRA* health risk assessment, *DWQI* drinking water quality index, *FTIR* fourier transform infrared technology, *SAR* sodium adsorption ratio, *LSI* langelier saturation index, *PI* permeability index, *HCA* hierarchical cluster analysis, *FA* factor analysis, *RRA* radiological risk assessment, *CTR* chemical toxicity risk, *HQ* hazard quotient, *CDI* chronic daily intake, *HI* hazard index, *EWQI* entropy water quality index, *HPI* heavy metal pollution index, *HCI* heavy metal contamination index, *HEI* heavy metal evaluation index, *XRD* X-ray diffraction, *TH* total hardness, *MI* metal index, *FGQI* fuzzy Logic with GIS-based groundwater quality index

Management of groundwater under climate change

Growing demand for water in every sector and the changing climatic conditions are the root causes of spatiotemporal variations in the availability of freshwater, which put a big challenge in front of water resources managers and environmentalists (Li and Qian 2018; Li and Wu 2019; Sarkar et al. 2020; Swain et al. 2020a, b and 2021a, b). Fostering extensive research on groundwater systems, integrated information systems, early disaster warning facilities, water conservation practices, proper management of existing resources, identification, implementation and evaluation of control-aimed options, etc., are some of the measures to be considered seriously. It was reported in the IPCC 4th Assessment report that the number of studies on groundwater under climate change is very limited. Moreover, the results of such studies are mostly site-specific (Parry et al. 2007). Therefore, further research on developing collective and specific strategies to reduce the harmful impacts of climate change on groundwater should be encouraged. Simultaneously, the measures suggested by the prior studies should also be taken into account. Holman et al. (2012) discussed the best practices to assess the climate change impacts on groundwater. Incorporating the projections from climate models, improving the hydrogeological coupling and considering socio-economic aspects into models were emphasized. A single climate model or a single scenario may not be able to project the climate accurately, and thus, it is advisable to use a multi-model multi-scenario approach. Proper consideration of model uncertainties, implications in selecting the downscaling method and the indirect impacts induced by climate change on groundwater recharge or withdrawal should also be taken into account. Gleeson et al. (2012) emphasized on the sustainability of groundwater uses to maintain equity amongst the generations. Adaptive management of groundwater is the need of the hour to accomplish the long-term goals, i.e., securing ecological integrity, quality water availability, etc. The backcasting method should be used for policy-framing and the sustainability goals should be achieved by public participatory initiatives. Gleick (2010) discussed the importance of developing a strategic plan for judicious usage of water resources over the arid and semi-arid regions of southwestern North America. The study urged to rethink the present water supply and demand management, especially under the changing climate, which is a major threat for sustainable water management. Rainwater harvesting, desalination of brackish groundwater, and improved institutional management were regarded as a solution to handle the future water demands. Falloon and Betts (2010) assessed the impacts of climate on water management and agriculture over Europe with a special focus on the adaptation and mitigation strategies. The trends of projected crop productivity are found to be diametrically opposite for Southern and Northern Europe. The study described how the European agricultural mitigation would be affected under the climate-induced hydrological changes. The study recommended integrated approaches to assess the future impacts of climate as it involves complex interactions between hydrosphere, atmosphere, and biosphere. Foster et al. (2009) discussed on the practical management of groundwater in a transboundary context through the Guarani aquifer initiative implemented over the Mercosur nations (Uruguay, Paraguay, Brazil, and Argentina). The study highlighted the effectiveness of the local level management of groundwater through legal provisions, pilot projects, and protection measures. The aquifer pollution by anthropogenic activities, future drivers of resource use, natural aquifer quality regime, recharge mechanisms, and hydrogeological characteristics of the groundwater system should be thoroughly investigated for devising proper planning and management of transboundary aquifers (Foster et al. 2009; Villar and Ribeiro 2011). Bosello et al. (2007) provided an economy-wide estimate of the implications of SLR and suggested that coastal protection leads to improvement in the economy. According to Taylor (2013a), efficient management of groundwater under climate change involves the development of models that can integrate the complex interactions between groundwater, climate, and human activity. As groundwater is a high-potential resource to improve the resilience of freshwater uses under changing climate, opportunities must be exploited for enhancing the groundwater recharge under changing hydro-meteorological regimes. The application of remote sensing and GIS has been influential in identifying the potential recharge zones over different regions (Haque et al. 2020; Jasrotia et al. 2018; Khan et al. 2020), which can be helpful for the planning and management of groundwater resources. Further, awareness should be created among people regarding the judicious extraction of groundwater and its sustainable use. Conjunctive uses of surface water and groundwater can be helpful, i.e., the usage of surface water during wet periods and groundwater during dry periods is likely to be beneficial in managing the available water resources (Sukhija 2008; Van Geen et al. 2008). Effective management of drought depends on groundwater as it increases the resilience of the system against droughts. Particularly, conjunctive use of surface water and groundwater is one of the effective practices for the drought-prone area (Kerebih and Keshari 2021; Khan et al. 2014; Singh et al. 2016).

India has witnessed an increase in the frequency and severity of droughts in recent decades (Swain et al. 2021a). Climate change is believed to intensify drought frequencies, and groundwater is a reliable backup source of water supply to meet the water demands from different sectors during drought (Langridge and Daniels 2017); however, overexploitation of groundwater resources causes seawater intrusion, land subsidence, and reduced base flow to streams, ultimately posing a danger to the long-term viability of groundwater resource (Afshar et al. 2021; Prusty and Farooq 2020). Further, groundwater-dependent ecosystems (e.g., shrublands, meadows, and riparian areas) mainly rely on the groundwater available near the surface (i.e., at a shallow depth), and these ecosystems are more vulnerable to climate change with rising air temperature, frequent drought events and anthropogenic activities like over-pumping (Huntington et al. 2016). Therefore, the implementation of stringent regulations to restrict groundwater overdrafting is the need of the hour. Sustainable management of groundwater advocates the necessary and immediate action for artificial recharge to maintain the groundwater reservoir and utilization policies in combination with the socio-cultural condition for regulation and maintenance of the groundwater systems. Different methods have been used for artificial groundwater recharge, which can be categorized into two types, i.e., direct methods (surface spreading techniques: flooding, ditch, and furrows method; runoff conservation structures: bench terracing, contour bunds, contour trenches, gully plugs, nalah bunds, check dams, percolation tanks, stream channel modification/augmentation; subsurface techniques: injection wells or recharge wells, gravity head recharge wells, recharge pits and shafts) and indirect methods (induced recharge, aquifer modification techniques) (CGWB 2007; Mukherjee 2016). Tiwari and Pal (2021) have provided an overview of recent trends in groundwater conservation with a focus on Indian regions.

As climate change has been argued as one of the potential factors in making the groundwater availability problems more critical, the approach of 'impact assessment' has been replaced by 'adaptation' to explore more coping strategies (Afshar et al. 2021). For example, studies (Khan et al. 2012; Safi et al. 2018) have recommended that SLR adaptation solutions should be mainstreamed into a coastal zone management and planning effort that incorporates all coastal natural resources (ecosystem-based adaptation) and the social communities that rely on them (community-based adaptation) through capacity building. Moreover, different plans and strategies have been suggested by researchers to effectively and sustainably manage groundwater resources, which can act as a drought reserve,i.e., storage of water meant to be utilized during droughts. The dry/drought periods can be sustainably managed by defining the unacceptable overdraft of groundwater resources, identifying the drought-prone area, studying the water budget in the drought-prone area, estimating the additional 'drought reserve' needed to avoid the groundwater level decline (from where it may fail to recover) (Langridge and Daniels 2017). The use of aquifers as natural storage reservoirs avoids several problems of evaporation losses and ecosystem impacts linked to surface-water reservoirs (Taylor et al. 2013a). In South Asia, the excessive abstraction of groundwater for irrigation in dry season has induced greater recharge in regions with permeable soils by enhancing the available groundwater storage during the subsequent monsoon (Shamsudduha et al. 2011). Similarly, the groundwater recharge in northern Europe is projected to increase during winters, which may be helpful to sustain anticipated increases in summer demand (Treidel et al. 2011).

In addition to all the above-mentioned facets of groundwater management, the expansion of the groundwater monitoring network is essential to understand the complex responses of climate on the groundwater system, which is impeded at present mainly due to a dearth of ground-based observations. Currently, the freely available groundwater data from CGWB is mostly limited to depth to water level and physicochemical parameters. The regular monitoring and availability of data for heavy metals and biological contaminants can boost groundwater research in India. Moreover, effective communication between policymakers and the scientific community should be bridged to frame practical/applicable management policies and take necessary actions. Further, different cultural factors like values, beliefs, and norms play an essential role in environmental management (Sanderson and Curtis 2016). Therefore, more research is needed to understand the complex relationships of the cultural and behavioral aspects of the population in the prospect of climate change risk assessment and decision in groundwater use at farm and household level. Bhattacharya and Bundschuh (2015) highlighted the significant role of groundwater in fulfilling the United Nations' sustainable development goals. Therefore, this study emphasizes framing policies that include climate change and groundwater governance, which must be implemented at the grassroots level, supporting sustainable development.

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Data availability This is a review paper and hence, data availability is not applicable. However, the data related to groundwater (depth to water level, quality) over the Indian region can be availed from the Central ground water Board (CGWB), Govt. of India.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interest.

References

Adimalla N (2019) Groundwater quality for drinking and irrigation purposes and potential health risks assessment: a case study from semi-arid region of South India. Expo Health 11:109–123. https://doi.org/10.1007/s12403-018-0288-8

Adimalla N (2020) Spatial distribution, exposure, and potential health risk assessment from nitrate in drinking water from semi-arid region of South India. Hum Ecol Risk Assess 26:310–334. https://doi.org/10.1080/10807039.2018.1508329

Adimalla N, Li P (2019) Occurrence, health risks, and geochemical mechanisms of fluoride and nitrate in groundwater of the rock-dominant semi-arid region, Telangana State India. Hum Ecol Risk Assess 25(1–2):81–103

Adimalla N, Qian H (2020) Spatial distribution and health risk assessment of fluoride contamination in groundwater of Telangana: a state-of-the-art. Geochemistry 80(4):125548

Adimalla N, Qian H (2021) Geospatial distribution and potential noncarcinogenic health risk assessment of nitrate contaminated groundwater in Southern India: a case study. Arch Environ Contam Toxicol 80(1):107–119

Adimalla N, Taloor AK (2020) Hydrogeochemical investigation of groundwater quality in the hard rock terrain of South India using geographic information system (GIS) and groundwater quality index (GWQI) techniques. Groundw Sustain Dev 10:100288

Adimalla N, Venkatayogi S (2018) Geochemical characterization and evaluation of groundwater suitability for domestic and agricultural utility in semi-arid region of Basara, Telangana State South India. Appl Water Sci 8:44

Adimalla N, Li P, Venkatayogi S (2018a) Hydrogeochemical evaluation of groundwater quality for drinking and irrigation purposes and integrated interpretation with water quality index studies. Environ Process 5(2):363–383

Adimalla N, Vasa SK, Li P (2018b) Evaluation of groundwater quality, Peddavagu in Central Telangana (PCT), South India: an insight of controlling factors of fluoride enrichment. Model Earth Syst Environ 4(2):841–852

Adimalla N, Qian H, Wang H (2019a) Assessment of heavy metal (HM) contamination in agricultural soil lands in northern Telangana, India: an approach of spatial distribution and multivariate statistical analysis. Environ Monit Assess 191:246

Adimalla N, Venkatayogi S, Das SV (2019b) Assessment of fluoride contamination and distribution: a case study from a rural part of Andhra Pradesh India. Appl Water Sci 9:94

Adimalla N, Dhakate R, Kasarla A, Taloor AK (2020) Appraisal of groundwater quality for drinking and irrigation purposes in Central Telangana India. Groundw Sustain Dev 10:100334

Adimalla N, Qian H, Tiwari DM (2021) Groundwater chemistry, distribution and potential health risk appraisal of nitrate enriched groundwater: a case study from the semi-urban region of South India. Ecotoxicol Environ Saf 207:111277

Afshar A, Khosravi M, Molajou A (2021) Assessing adaptability of cyclic and non-cyclic approach to conjunctive use of groundwater and surface water for sustainable management plans under climate change. Water Resour Manage 35(11):3463–3479. https://doi.org/10.1007/s11269-021-02887-3

Aggarwal A, Soni J, Sharma K, Sapra M, Chitrakshi KO, Haritash AK (2020) Hydrogeochemical assessment of groundwater for drinking and agricultural use: a case study of rural areas of Alwar, Rajasthan. Environ Manage 67:513–521. https://doi.org/10.1007/s00267-020-01361-x

Ahada CPS, Suthar S (2017) Hydrochemistry of groundwater in North Rajasthan, India: chemical and multivariate analysis. Environ Earth Sci 76:203. https://doi.org/10.1007/s12665-017-6496-x

Aladejana JA, Kalin RM, Sentenac P, Hassan I (2020) Assessing the impact of climate change on groundwater quality of the shallow coastal aquifer of eastern Dahomey Basin Southwestern Nigeria. Water 12(1):224

Ali R, McFarlane D, Varma S, Dawes W, Emelyanova I, Hodgson G, Charles S (2012) Potential climate change impacts on groundwater resources of south-western Australia. J Hydrol 475:456–472

Ali S, Shekhar S, Chandrasekhar T, Yadav AK, Arora NK, Kashyap CA, Bhattacharya P, Rai SP, Pande P, Chandrasekharam D (2021) Influence of the water–sediment interaction on the major ions chemistry and fluoride pollution in groundwater of the older Alluvial Plains of Delhi India. J Earth Syst Sci 130(2):98

Allan RP, Soden BJ (2008) Atmospheric warming and the amplification of precipitation extremes. Science 321(5895):1481–1484

Allen DM, Whitfield PH, Werner A (2010) Groundwater level responses in temperate mountainous terrain: regime classification, and linkages to climate and streamflow. Hydrol Process 24(23):3392–3412

Aravinthasamy P, Karunanidhi D, Subramani T, Anand B, Roy PD, Srinivasamoorthy K (2020) Fluoride contamination in groundwater of the Shanmuganadhi River basin (south India) and its association with other chemical constituents using geographical information system and multivariate statistics. Geochemistry 80(4):125555. https://doi.org/10.1016/j.chemer.2019.125555

Ashbolt NJ, Grabow WO, Snozzi M (2001) Indicators of microbial water quality. In: Fewtrell L, Bartram J (eds) Water quality–Guidelines, standards and health: Assessment of risk and risk management for water-related infectious disease. World Health Organization, pp 289–316

Asoka A, Gleeson T, Wada Y, Mishra V (2017) Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India. Nat Geosci 10(2):109–117

Asoka A, Wada Y, Fishman R, Mishra V (2018) Strong linkage between precipitation intensity and monsoon season groundwater recharge in India. Geophys Res Lett 45(11):5536–5544

Babiker IS, Mohamed MA, Terao H, Kato K, Ohta K (2004) Assessment of groundwater contamination by nitrate leaching from intensive vegetable cultivation using geographical information system. Environ Int 29(8):1009–1017

Bahita TA, Swain S, Dayal D, Jha PK, Pandey A (2021a) Water quality assessment of Upper Ganga Canal for human drinking. In: Pandey A, Mishra SK, Kansal ML, Singh RD, Singh VP (eds) Climate impacts on water resources in India. Springer, Cham, pp 371–392. https://doi.org/10.1007/978-3-030-51427-3_28

Bahita TA, Swain S, Pandey P, Pandey A (2021b) Assessment of heavy metal contamination in livestock drinking water of Upper Ganga Canal (Roorkee City, India). Arab J Geosci 14:2861. https://doi.org/10.1007/s12517-021-08874-7

Bahita TA (2019) Water quality assessment and pollution status of Upper Ganga Canal. PhD Thesis, Indian Institute of Technology Roorkee

Bajwa BS, Kumar S, Singh S, Sahoo SK, Tripathi RM (2017) Uranium and other heavy toxic elements distribution in the drinking water samples of SW-Punjab, India. J Radiat Res Appl Sci 10:13–19. https://doi.org/10.1016/j.jrras.2015.01.002

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (2008) Climate change and water. Technical paper of the Intergovernmental Panel on Climate Change, Geneva

Bhanja SN, Mukherjee A (2019) In situ and satellite-based estimates of usable groundwater storage across India: implications for drinking water supply and food security. Adv Water Resour 126:15–23

Bhanja SN, Mukherjee A, Saha D, Velicogna I, Famiglietti JS (2016) Validation of GRACE based groundwater storage anomaly using in-situ groundwater level measurements in India. J Hydrol 543:729–738

Bhanja SN, Mukherjee A, Rodell M, Wada Y, Chattopadhyay S, Velicogna I, Pangaluru K, Famiglietti JS (2017a) Groundwater rejuvenation in parts of India influenced by water-policy change implementation. Sci Rep 7(1):1–7

Bhanja SN, Rodell M, Li B, Saha D, Mukherjee A (2017b) Spatio-temporal variability of groundwater storage in India. J Hydrol 544:428–437

Bhanja SN, Malakar P, Mukherjee A, Rodell M, Mitra P, Sarkar S (2019a) Using satellite-based vegetation cover as indicator of groundwater storage in natural vegetation areas. Geophys Res Lett 46(14):8082–8092

Bhanja SN, Mukherjee A, Rangarajan R, Scanlon BR, Malakar P, Verma S (2019b) Long-term groundwater recharge rates across India by in situ measurements. Hydrol Earth Syst Sci 23(2):711–722

Bhanja SN, Mukherjee A, Rodell M (2020) Groundwater storage change detection from in situ and GRACE-based estimates in major river basins across India. Hydrol Sci J 65(4):650–659

Bhattacharya P, Bundschuh J (2015) Groundwater for sustainable development-cross cutting the UN sustainable development goals. Groundw Sustain Dev 1(1–2):155–157

Bloomfield JP, Williams RJ, Gooddy DC, Cape JN, Guha PM (2006) Impacts of climate change on the fate and behaviour of pesticides in surface and groundwater—a UK perspective. Sci Total Environ 369(1–3):163–177

Bosello F, Roson R, Tol RS (2007) Economy-wide estimates of the implications of climate change: sea level rise. Environ Resource Econ 37(3):549–571

Cartwright I, Weaver TR, Stone D, Reid M (2007) Constraining modern and historical recharge from bore hydrographs, 3H, 14C, and chloride concentrations: applications to dual-porosity aquifers in dryland salinity areas, Murray Basin. Aust J Hydrol 332(1–2):69–92

CGWB (2007) Manual on artificial recharge of ground water. Central Ground Water Board Ministry of Water Resources, Government of India, Faridabad

CGWB (2012) Aquifer systems of India. Central Ground Water Board Ministry of Water Resources, Government of India, Faridabad

CGWB (2018) Groundwater quality in shallow aquifers in India. Central Ground Water Board Ministry of Water Resources River Development and Ganga Rejuvenation, Government of India, Faridabad

CGWB (2020a) Ground water year book–India 2019–20. Central Ground Water Board Ministry of Jal Shakti, Government of India, Faridabad

CGWB (2020b) Uranium occurrence in shallow aquifers in India. Central Ground Water Board Ministry of Jal Shakti, Government of India, Faridabad

Chatterjee D, Halder D, Majumder S, Biswas A, Nath B, Bhattacharya P, Bhowmick S, Mukherjee-Goswami A, Saha D, Hazra R, Maity PB (2010) Assessment of arsenic exposure from groundwater and rice in Bengal Delta Region, West Bengal. India Water Res 44(19):5803–5812

Chen J (2010) Holistic assessment of groundwater resources and regional environmental problems in the North China Plain. Environ Earth Sci 61(5):1037–1047

Cullet P, Bhullar L, Koonan S (2017) Regulating the interactions between climate change and groundwater: lessons from India. Water Int 42(6):646–662

Cuthbert MO, Gleeson T, Moosdorf N, Befus KM, Schneider A, Hartmann J, Lehner B (2019) Global patterns and dynamics of climate–groundwater interactions. Nat Clim Chang 9(2):137–141

Dahiya S, Singh B, Gaur S, Garg VK, Kushwaha HS (2007) Analysis of groundwater quality using fuzzy synthetic evaluation. J Hazard Mater 147(3):938–946

Dalias P, Anderson JM, Bottner P, Coûteaux MM (2001) Long-term effects of temperature on carbon mineralisation processes. Soil Biol Biochem 33(7–8):1049–1057

Dalin C, Wada Y, Kastner T, Puma MJ (2017) Groundwater depletion embedded in international food trade. Nature 543(7647):700–704

Dhal L, Swain S (2022) Understanding and modeling the process of seawater intrusion: a review. In: Gupta P, Yadav B, Himansh S (eds) Advances in remediation techniques for polluted soils and groundwater. Elsevier, Netherlands, pp 269–290

Döll P (2002) Impact of climate change and variability on irrigation requirements: a global perspective. Clim Change 54(3):269–293

Döll P (2009) Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. Environ Res Lett 4(3):035006

Döll P, Fiedler K (2008) Global-scale modeling of groundwater recharge. Hydrol Earth Syst Sci 12:863–885

Döll P, Hoffmann-Dobrev H, Portmann FT, Siebert S, Eicker A, Rodell M, Strassberg G, Scanlon BR (2012) Impact of water withdrawals from groundwater and surface water on continental water storage variations. J Geodyn 59:143–156

Dwarakish GS, Vinay SA, Natesan U, Asano T, Kakinuma T, Venkataramana K, Pai BJ, Babita MK (2009) Coastal vulnerability assessment of the future sea level rise in Udupi coastal zone of Karnataka state, west coast of India. Ocean Coast Manag 52(9):467–478

Earman S, Dettinger M (2011) Potential impacts of climate change on groundwater resources–a global review. J Water Clim Change 2(4):213–229

Eckhardt K, Ulbrich U (2003) Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range. J Hydrol 284(1–4):244–252

EPA (2001) Parameters of water quality: interpretation and standards. Environmental Protection Agency, Ireland

Essefi E, Tagorti MA, Touir J, Yaich C (2013) Hydrocarbons migration through groundwater convergence toward saline depressions: a case study, Sidi El Hani discharge playa Tunisian Sahel. Int Sch Res Not 2013:709190

Falloon P, Betts R (2010) Climate impacts on European agriculture and water management in the context of adaptation and mitigation—the importance of an integrated approach. Sci Total Environ 408(23):5667–5687

Famiglietti JS, Lo M, Ho SL, Bethune J, Anderson KJ, Syed TH, Swenson SC, de Linage CR, Rodell M (2011) Satellites measure recent rates of groundwater depletion in California's Central Valley. Geophys Res Lett 38(3):L03403

Faunt CC (2009) Groundwater availability of the Central Valley Aquifer, California. Professional Paper 1766, US Geological Survey

Favreau G, Cappelaere B, Massuel S, Leblanc M, Boucher M, Boulain N, Leduc C (2009) Land clearing, climate variability, and water resources increase in semiarid southwest Niger: a review. Water Resour Res 45(7):W00A16

Ferguson G, Gleeson T (2012) Vulnerability of coastal aquifers to groundwater use and climate change. Nat Clim Chang 2(5):342–345

Field CB, Barros V, Stocker TF, Dahe Q (eds) (2012) Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Foster S, Hirata R, Vidal A, Schmidt G, Garduño H (2009) The guarani aquifer initiative—towards realistic groundwater management in a transboundary context. World Bank, Washington, DC

Gambrell RP (1994) Trace and toxic metals in wetlands—a review. J Environ Qual 23(5):883–891

Ghosh M, Pal DK, Santra SC (2020) Spatial mapping and modeling of arsenic contamination of groundwater and risk assessment

through geospatial interpolation technique. Environ Dev Sustain 22:2861–2880. https://doi.org/10.1007/s10668-019-00322-7
Girotto M, De Lannoy GJ, Reichle RH, Rodell M, Draper C, Bhanja SN, Mukherjee A (2017) Benefits and pitfalls of GRACE data assimilation: A case study of terrestrial water storage depletion in India. Geophys Res Lett 44(9):4107–4115
Gleeson T, Alley WM, Allen DM, Sophocleous MA, Zhou Y, Taniguchi M, VanderSteen J (2012) Towards sustainable groundwater use: setting long-term goals, backcasting, and managing adaptively. Groundwater 50(1):19–26
Gleick PH (2010) Roadmap for sustainable water resources in southwestern North America. Proc Natl Acad Sci 107(50):21300–21305
Goel, P. K. (2006). Water Pollution: Cause, Effects and Control. Revised Second Edition, New Age International Pvt Ltd.
Goldin T (2016) India's drought below ground. Nat Geosci 9(2):98–98
Green TR (2016) Linking climate change and groundwater. In: Jakeman AJ, Barreteau O, Hunt RJ, Rinaudo J-D, Ross A (eds) Integrated groundwater management. Springer, Cham, pp 97–141
Green TR, Taniguchi M, Kooi H, Gurdak JJ, Allen DM, Hiscock KM, Treidel H, Aureli A (2011) Beneath the surface of global change: impacts of climate change on groundwater. J Hydrol 405(3–4):532–560
Gupta PK (2020) Pollution load on Indian soil-water systems and associated health hazards: a review. J Environ Eng 146(5):03120004
Gupta D, Dhanya CT (2020) The potential of GRACE in assessing the flood potential of Peninsular Indian River basins. Int J Remote Sens 41(23):9009–9038
Gupta PK, Sharma D (2019) Assessment of hydrological and hydrochemical vulnerability of groundwater in semi-arid region of Rajasthan India. Sustain Water Resour Manage 5(2):847–861
Guptha GC, Swain S, Al-Ansari N, Taloor AK, Dayal D (2021) Evaluation of an urban drainage system and its resilience using remote sensing and GIS. Remote Sens Appl Soc Environ 23:100601. https://doi.org/10.1016/j.rsase.2021.100601
Guptha GC, Swain S, Al-Ansari N, Taloor AK, Dayal D (2022) Assessing the role of SuDS in resilience enhancement of urban drainage system: a case study of Gurugram City India. Urb Clim 41:101075. https://doi.org/10.1016/j.uclim.2021.101075
Hamed Y, Hadji R, Redhaounia B, Zighmi K, Bâali F, El Gayar A (2018) Climate impact on surface and groundwater in North Africa: a global synthesis of findings and recommendations. Euro-Mediterr J Environ Integr 3(1):25
Han W, Meehl GA, Rajagopalan B, Fasullo JT, Hu A, Lin J, Large WG, Wang JW, Quan XW, Trenary LL, Wallcraft A (2010) Patterns of Indian Ocean sea-level change in a warming climate. Nat Geosci 3(8):546–550
Hanson RT, Flint LE, Flint AL, Dettinger MD, Faunt CC, Cayan D, Schmid W (2012) A method for physically based model analysis of conjunctive use in response to potential climate changes. Water Resour Res 48(6):W00L08
Haque S, Kannaujiya S, Taloor AK, Keshri D, Bhunia RK, Ray PKC, Chauhan P (2020) Identification of groundwater resource zone in the active tectonic region of Himalaya through earth observatory techniques. Groundw Sustain Dev 10:100337
He S, Li P, Wu J, Elumalai V, Adimalla N (2020) Groundwater quality under land use/land cover changes: a temporal study from 2005 to 2015 in Xi'an, northwest China. Hum Ecol Risk Assess 26(10):2771–2797
Herrera-Pantoja M, Hiscock KM, Boar RR (2012) The potential impact of climate change on groundwater-fed wetlands in eastern England. Ecohydrology 5(4):401–413
Holman IP (2006) Climate change impacts on groundwater recharge-uncertainty, shortcomings, and the way forward? Hydrogeol J 14(5):637–647
Holman IP, Allen DM, Cuthbert MO, Goderniaux P (2012) Towards best practice for assessing the impacts of climate change on groundwater. Hydrogeol J 20(1):1–4
Hundal HS, Singh K, Singh D (2009) Arsenic content in ground and canal water of Punjab N-W India. Environ Monit Assess 154(1–4):393–400
Huntington J, McGwire K, Morton C, Snyder K, Peterson S, Erickson T, Niswonger R, Carroll R, Smith G, Allen R (2016) Assessing the role of climate and resource management on groundwater dependent ecosystem changes in arid environments with the Landsat archive. Remote Sens Environ 185:186–197. https://doi.org/10.1016/j.rse.2016.07.004
Jain SK (2011) Population rise and growing water scarcity in India–revised estimates and required initiatives. Curr Sci 101(3):271–276
Jain SK, Agarwal PK, Singh VP (2007) Hydrology and water resources of India. Water Science and Technology Library Series, vol 57. Springer Science & Business Media, Germany
Jasrotia AS, Taloor AK, Andotra U, Bhagat BD (2018) Geoinformatics based groundwater quality assessment for domestic and irrigation uses of the Western Doon valley, Uttarakhand, India. Groundw Sustain Dev 6:200–212
Jasrotia AS, Taloor AK, Andotra U, Kumar R (2019) Monitoring and assessment of groundwater quality and its suitability for domestic and agricultural use in the Cenozoic rocks of Jammu Himalaya, India: a geospatial technology based approach. Groundw Sustain Dev 8:554–566
Jean JS, Guo HR, Chen SH, Liu CC, Chang WT, Yang YJ, Huang MC (2006) The association between rainfall rate and occurrence of an enterovirus epidemic due to a contaminated well. J Appl Microbiol 101(6):1224–1231
Jha MK, Shekhar A, Jenifer MA (2020) Assessing groundwater quality for drinking water supply using hybrid fuzzy-GIS-based water quality index. Water Res 179:115867. https://doi.org/10.1016/j.watres.2020.115867
Kanmani S, Gandhimathi R (2013) Investigation of a physicochemical characteristics heavy metal distribution profile in groundwater system around the open dump site. Appl Wat Sci 3(2):387–399
Karunakalage A, Kannaujiya S, Chatterjee RS, Taloor AK, Pranjal P, Chauhan P, Ray PKC, Kumar S (2021a) Groundwater storage assessment using effective downscaling grace data in water-stressed regions of India. In: Taloor AK, Kotlia BS, Kumar K (eds) Water, cryosphere, and climate change in the Himalayas: a geospatial approach. Springer, pp 217–226. https://doi.org/10.1007/978-3-030-67932-3_14
Karunakalage A, Sarkar T, Kannaujiya S, Chauhan P, Pranjal P, Taloor AK, Kumar S (2021b) The appraisal of groundwater storage dwindling effect, by applying high resolution downscaling GRACE data in and around Mehsana district, Gujarat India. Groundw Sustain Dev 13:100559
Kaur S, Kaur J (2015) Assessment of seasonal variations in oxygen demanding parameters (DO, BOD, COD) along Sirhind Canal passing through Moga, Punjab India. Int J Innov Sci Eng Technol 2(5):697–700
Kerebih MS, Keshari AK (2021) Distributed simulation-optimization model for conjunctive use of groundwater and surface water under environmental and sustainability restrictions. Water Resour Manage 35(8):2305–2323. https://doi.org/10.1007/s11269-021-02788-5
Khalaj M, Kholghi M, Saghafian B, Bazrafshan J (2019) Impact of climate variation and human activities on groundwater quality in northwest of Iran. J Water Supply Res Technol AQUA 68(2):121–135
Khan AS, Ramachandran A, Usha N, Punitha S, Selvam V (2012) Predicted impact of the sea-level rise at Vellar-Coleroon estuarine

region of Tamil Nadu coast in India: mainstreaming adaptation as a coastal zone management option. Ocean Coast Manag 69:327–339

Khan MR, Voss CI, Yu W, Michael HA (2014) Water resources management in the Ganges Basin: a comparison of three strategies for conjunctive use of groundwater and surface water. Water Resour Manage 28(5):1235–1250. https://doi.org/10.1007/s11269-014-0537-y

Khan A, Govil H, Taloor AK, Kumar G (2020) Identification of artificial groundwater recharge sites in parts of Yamuna river basin India based on remote sensing and geographical information system. Groundw Sustain Dev 11:100415

Konikow LF (2011) Contribution of global groundwater depletion since 1900 to sea-level rise. Geophys Res Lett 38(17):L17401

Krishan G, Kumar B, Sudarsan N, Rao MS, Ghosh NC, Taloor AK, Bhattacharya P, Singh S, Kumar CP, Sharma A, Jain SK (2021) Isotopes (δ18O, δD and 3H) variations in groundwater with emphasis on salinization in the state of Punjab India. Sci Total Environ 789:148051

Kumar A, Nirpen L, Ranjan A, Gulati K, Thakur S, Jindal T (2014a) Microbial groundwater contamination and effective monitoring system. Asian J Eviron Sci 9:37–48

Kumar A, Rout S, Mishra MK, Ravi PM, Tripathi RM, Ghosh AK (2014b) Characterization of groundwater composition in Punjab state with special emphasis on uranium content, speciation and mobility. Radiochim Acta 102(3):239–254

Kumar D, Singh AK, Taloor AK, Singh DS (2021a) Recessional pattern of Thelu and Swetvarn glaciers between 1968 and 2019, Bhagirathi basin, Garhwal Himalaya, India. Quatern Int 575–576:227–235

Kumar KS, Rathnam EV, Sridhar V (2021b) Tracking seasonal and monthly drought with GRACE-based terrestrial water storage assessments over major river basins in South India. Sci Total Environ 763:142994

Kurylyk BL, MacQuarrie KT, McKenzie JM (2014) Climate change impacts on groundwater and soil temperatures in cold and temperate regions: implications, mathematical theory, and emerging simulation tools. Earth Sci Rev 138:313–334

Langridge R, Daniels B (2017) Accounting for climate change and drought in implementing sustainable groundwater management. Water Resour Manage 31(11):3287–3298. https://doi.org/10.1007/s11269-017-1607-8

Leblanc MJ, Favreau G, Massuel S, Tweed SO, Loireau M, Cappelaere B (2008) Land clearance and hydrological change in the Sahel: SW Niger. Glob Planet Ch 61(3–4):135–150

Leblanc MJ, Tregoning P, Ramillien G, Tweed SO, Fakes A (2009) Basin-scale, integrated observations of the early 21st century multiyear drought in southeast Australia. Water Resour Res 45(4):W04408

Leblanc M, Tweed S, Van Dijk A, Timbal B (2012) A review of historic and future hydrological changes in the Murray-Darling Basin. Glob Planet Ch 80:226–246

Li R (2016) Assessing groundwater pollution risk in response to climate change and variability. In: Fares Al (ed) Emerging issues in groundwater resources. Springer, Cham, pp 31–50

Li R, Merchant JW (2013) Modeling vulnerability of groundwater to pollution under future scenarios of climate change and biofuels-related land use change: a case study in North Dakota, USA. Sci Total Environ 447:32–45

Li P, Qian H (2018) Water resources research to support a sustainable China. Int J Water Resour Dev 34(3):327–336

Li P, Wu J (2019) Sustainable living with risks: meeting the challenges. Hum Ecol Risk Assess 25(1–2):1–10

Li P, Wu J, Qian H, Lyu X, Liu H (2014) Origin and assessment of groundwater pollution and associated health risk: a case study in an industrial park, northwest China. Environ Geochem Health 36(4):693–712

Li P, Wu J, Qian H (2016) Preliminary assessment of hydraulic connectivity between river water and shallow groundwater and estimation of their transfer rate during dry season in the Shidi River China. Environ Earth Sci 75(2):99

Li P, Tian R, Xue C, Wu J (2017) Progress, opportunities, and key fields for groundwater quality research under the impacts of human activities in China with a special focus on western China. Environ Sci Pollut Res 24(15):13224–13234

Li B, Rodell M, Kumar S, Beaudoing HK, Getirana A, Zaitchik BF, de Goncalves LG, Cossetin C, Bhanja S, Mukherjee A, Tian S et al (2019) Global GRACE data assimilation for groundwater and drought monitoring: advances and challenges. Water Resour Res 55(9):7564–7586

Long D, Chen X, Scanlon BR, Wada Y, Hong Y, Singh VP, Chen Y, Wang C, Han Z, Yang W (2016) Have GRACE satellites overestimated groundwater depletion in the Northwest India aquifer? Sci Rep 6:24398

Longuevergne L, Scanlon BR, Wilson CR (2010) GRACE hydrological estimates for small basins: evaluating processing approaches on the high plains aquifer, USA. Water Resour Res 46(11):W11517

Machiwal D, Jha MK, Mal BC (2011) GIS-based assessment and characterization of groundwater quality in a hard-rock hilly terrain of Western India. Environ Monit Assess 174:645–663. https://doi.org/10.1007/s10661-010-1485-5

Maity S, Biswas R, Sarkar A (2020) Comparative valuation of groundwater quality parameters in Bhojpur Bihar for arsenic risk assessment. Chemosphere 259:127398

Malakar P, Mukherjee A, Bhanja SN, Ganguly AR, Ray RK, Zahid A, Sarkar S, Saha D, Chattopadhyay S (2021) Three decades of depth-dependent groundwater response to climate variability and human regime in the transboundary Indus-Ganges-Brahmaputra-Meghna mega river basin aquifers. Adv Water Resour 149:103856

Manning AH, Verplanck PL, Caine JS, Todd AS (2013) Links between climate change, water-table depth, and water chemistry in a mineralized mountain watershed. Appl Geochem 37:64–78

Marghade D, Malpe DB, Duraisamy K, Patil PD, Li P (2020) Hydrogeochemical evaluation, suitability, and health risk assessment of groundwater in the watershed of Godavari basin, Maharashtra, Central India. Environ Sci Pollut Res 28:18471–18494. https://doi.org/10.1007/s11356-020-10032-7

Mas-Pla J, Menció A (2019) Groundwater nitrate pollution and climate change: learnings from a water balance-based analysis of several aquifers in a western Mediterranean region (Catalonia). Environ Sci Pollut Res 26(3):2184–2202

McGill BM, Altchenko Y, Hamilton SK, Kenabatho PK, Sylvester SR, Villholth KG (2019) Complex interactions between climate change, sanitation, and groundwater quality: a case study from Ramotswa Botswana. Hydrogeol J 27(3):997–1015

McLeman R (2019) International migration and climate adaptation in an era of hardening borders. Nat Clim Chang 9(12):911–918

Mishra V, Asoka A, Vatta K, Lall U (2018) Groundwater depletion and associated CO_2 emissions in India. Earth's Future 6(12):1672–1681

Morsy KM, Alenezi A, AlRukaibi DS (2017) Groundwater and dependent ecosystems: revealing the impacts of climate change. Int J Appl Eng Res 12(13):3919–3926

Moseki MC (2017) Climate change impacts on groundwater: literature review. Environ Risk Assess Remediat 2(1):16–20

Mukherjee D (2016) A review on artificial groundwater recharge in India. SSRG Int J Civ Eng 3(1):57–62. https://doi.org/10.14445/23488352/ijce-v3i1p108

Mukherjee A, Bhanja SN (2019) An untold story of groundwater replenishment in India: impact of long-term policy interventions. In: Singh A, Saha D, Tyagi AC (eds) Water governance: challenges and prospects. Springer, Singapore, pp 205–218

Mukherjee A, Fryar AE (2008) Deeper groundwater chemistry and geochemical modeling of the arsenic affected western Bengal basin, West Bengal India. Appl Geochem 23(4):863–894

Mukherjee A, Fryar AE, Scanlon BR, Bhattacharya P, Bhattacharya A (2011) Elevated arsenic in deeper groundwater of the western Bengal basin, India: extent and controls from regional to local scale. Appl Geochem 26(4):600–613

Mukherjee A, Saha D, Harvey CF, Taylor RG, Ahmed KM, Bhanja SN (2015) Groundwater systems of the Indian sub-continent. J Hydrol Reg Stud 4:1–4

Mukherjee A, Fryar AE, Eastridge EM, Nally RS, Chakraborty M, Scanlon BR (2018) Controls on high and low groundwater arsenic on the opposite banks of the lower reaches of River Ganges, Bengal basin, India. Sci Total Environ 645:1371–1387

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, ISBN 978–981–10–3888–4, Singapore, p 799

Nair AS, Indu J (2020) Changing groundwater storage trend of India after severe drought. Int J Remote Sens 41(19):7565–7584

Narsimha A, Sudarshan V (2017a) Assessment of fluoride contamination in groundwater from Basara, Adilabad district, Telangana state India. Appl Water Sci 7(6):2717–2725

Narsimha A, Sudarshan V (2017b) Contamination of fluoride in groundwater and its effect on human health: a case study in hard rock aquifers of Siddipet, Telangana State India. Appl Water Sci 7(5):2501–2512

Nishy P, Saroja R (2018) A scientometric examination of the water quality research in India. Environ Monit Assess 190:225

NRC (2004) Indicators for waterborne pathogens. National Academies Press, National Research Council, Washington, DC

Obeidat MM, Awawdeh M, Al-Mughaid H (2013) Impact of a domestic wastewater treatment plant on groundwater pollution, north Jordan. Revis Mex De Cienc Geol 30(2):371–384

Omer NH (2019) Water quality parameters. In: Summers JK (eds) Water quality– science, assessments and policy. IntechOpen, pp 1–18. https://doi.org/10.5772/intechopen.89657

Oude Essink GHP, Van Baaren ES, De Louw PG (2010) Effects of climate change on coastal groundwater systems: a modeling study in the Netherlands. Water Resour Res 46(10):W00F04

Owor M, Taylor RG, Tindimugaya C, Mwesigwa D (2009) Rainfall intensity and groundwater recharge: empirical evidence from the Upper Nile Basin. Environ Res Lett 4(3):035009

Panda DK, Wahr J (2016) Spatiotemporal evolution of water storage changes in I ndia from the updated GRACE-derived gravity records. Water Resour Res 52(1):135–149

Pandey PK, Kass PH, Soupir ML, Biswas S, Singh VP (2014) Contamination of water resources by pathogenic bacteria. AMB Expr 4(1):1–6

Panwar S, Chakrapani GJ (2013) Climate change and its influence on groundwater resources. Curr Sci 105(1):37–46

Parry M, Parry ML, Canziani O, Palutikof J, Van der Linden P, Hanson C (eds) (2007) Climate change 2007-impacts, adaptation and vulnerability: working group II contribution to the fourth assessment report of the IPCC, vol 4. Cambridge University Press

Pokhrel YN, Hanasaki N, Yeh PJ, Yamada TJ, Kanae S, Oki T (2012) Model estimates of sea-level change due to anthropogenic impacts on terrestrial water storage. Nat Geosci 5(6):389–392

Pool DR (2005) Variations in climate and ephemeral channel recharge in southeastern Arizona United States. Water Resour Res 41(11):W11403

Prajapati M, Jariwala N, Agnihotri P (2017) Spatial distribution of groundwater quality with special emphasis on fluoride of Mandvi Taluka, Surat, Gujarat, India. Appl Water Sci 7:4735–4742

Prusty P, Farooq SH (2020) Seawater intrusion in the coastal aquifers of India-A review. HydroResearch 3:61–74. https://doi.org/10.1016/j.hydres.2020.06.001

Rajkumar H, Naik PK, Rishi MS (2020) A new indexing approach for evaluating heavy metal contamination in groundwater. Chemosphere 245:125598. https://doi.org/10.1016/j.chemosphere.2019.125598

Raju NJ, Dey S, Gossel W, Wycisk P (2012) Fluoride hazard and assessment of groundwater quality in the semi-arid Upper Panda River basin, Sonbhadra district, Uttar Pradesh India. Hydrol Sci J 57(7):1433–1452

Rao KN, Subraelu P, Venkateswara Rao T, Hema Malini B, Ratheesh R, Bhattacharya S, Rajawat AS (2008) Sea-level rise and coastal vulnerability: an assessment of Andhra Pradesh coast, India through remote sensing and GIS. J Coast Conserv 12(4):195–207

Rao PVN, Appa Rao S, Subba Rao N (2017) Geochemical evolution of groundwater in the western delta region of river Godavari, Andhra Pradesh, India. Appl Water Sci 7:813–822

Reza R, Singh G (2009) Physico-chemical analysis of groundwater in Angul-Talcher region of Orissa. India J Am Sci 5(5):53–58

Rivett MO, Buss SR, Morgan P, Smith JW, Bemment CD (2008) Nitrate attenuation in groundwater: a review of biogeochemical controlling processes. Water Res 42(16):4215–4232

Rodell M, Velicogna I, Famiglietti JS (2009) Satellite-based estimates of groundwater depletion in India. Nature 460(7258):999–1002

Sackaria M, Elango L (2020) Organic micropollutants in groundwater of India—a review. Water Environ Res 92(4):504–523

Safi A, Rachid G, El-Fadel M, Doummar J, Abou Najm M, Alameddine I (2018) Synergy of climate change and local pressures on saltwater intrusion in coastal urban areas: effective adaptation for policy planning. Water Int 43(2):145–164

Saha D, Shekhar S, Ali S, Elango L, Vittala S (2020) Recent scientific perspectives on the Indian hydrogeology. Proc Indian Natl Sci Acad 86(1):459–478

Sahoo S, Kaur A, Litoria P, Pateriya B (2014) Geospatial modelling for groundwater quality mapping: a case study of Rupnagar district, Punjab, India. Int Arch Photogramm Remote Sens Sp Inf Sci 40(8):227–232

Sahoo S, Swain S, Goswami A, Sharma R, Pateriya B (2021) Assessment of trends and multi-decadal changes in groundwater level in parts of the Malwa region, Punjab India. Groundw Sustain Dev 14:100644. https://doi.org/10.1016/j.gsd.2021.100644

Saji AP, Sunil PS, Sreejith KM, Gautam PK, Kumar KV, Ponraj M, Amirtharaj S, Shaju RM, Begum SK, Reddy CD, Ramesh DS (2020) Surface deformation and influence of hydrological mass over Himalaya and North India revealed from a decade of continuous GPS and GRACE observations. J Geophys Res Earth Surf 125(1):e2018JF004943

Sakram G, Adimalla N (2018) Hydrogeochemical characterization and assessment of water suitability for drinking and irrigation in crystalline rocks of Mothkur region, Telangana State South India. App Water Sci 8(5):143

Sakram G, Kuntamalla S, Machender G, Dhakate R, Narsimha A (2019) Multivariate statistical approach for the assessment of fluoride and nitrate concentration in groundwater from Zaheerabad area, Telangana State India. Sustain Water Resour Manage 5(2):785–796

Sanderson MR, Curtis AL (2016) Culture, climate change and farm-level groundwater management: an Australian case study. J Hydrol 536:284–292

Sarkar T, Kannaujiya S, Taloor AK, Ray PKC, Chauhan P (2020) Integrated study of GRACE data derived interannual groundwater storage variability over water stressed Indian regions. Groundw Sustain Dev 10:100376

Scanlon BR, Levitt DG, Reedy RC, Keese KE, Sully MJ (2005) Ecological controls on water-cycle response to climate variability in deserts. Proc Natl Acad Sci 102(17):6033–6038

Scanlon BR, Keese KE, Flint AL, Flint LE, Gaye CB, Edmunds WM, Simmers I (2006) Global synthesis of groundwater recharge in semiarid and arid regions. Hydrol Process 20(15):3335–3370

Scanlon BR, Gates JB, Reedy RC, Jackson WA, Bordovsky JP (2010) Effects of irrigated agroecosystems: 2. Quality of soil water and

groundwater in the southern high plains Texas. Water Resour Res 46(9):09538
Scanlon BR, Faunt CC, Longuevergne L, Reedy RC, Alley WM, McGuire VL, McMahon PB (2012a) Groundwater depletion and sustainability of irrigation in the US high plains and Central Valley. Proc Natl Acad Sci 109(24):9320–9325
Scanlon BR, Longuevergne L, Long D (2012b) Ground referencing GRACE satellite estimates of groundwater storage changes in the California Central Valley, USA. Water Resour Res 48(4):W04520
Scibek J, Allen DM (2006) Modeled impacts of predicted climate change on recharge and groundwater levels. Water Resour Res 42(11):W11405
Semwal N, Alkolkar P (2011) Suitability of irrigation water quality of canals in NCR Delhi. Int J Basic Appl Chem Sci 1(1):60–69
Shamsudduha M, Taylor RG, Ahmed KM, Zahid A (2011) The impact of intensive groundwater abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh. Hydrogeol J 19(4):901–916
Shamsudduha M, Taylor RG, Longuevergne L (2012) Monitoring groundwater storage changes in the highly seasonal humid tropics: validation of GRACE measurements in the Bengal Basin. Water Resour Res 48(2):W02508
Shamsudduha M, Zahid A, Burgess WG (2019) Security of deep groundwater against arsenic contamination in the Bengal Aquifer System: a numerical modeling study in southeast Bangladesh. Sustain Water Resour Manage 5(3):1073–1087
Shetye SR, Gouveia AD, Pathak MC (1990) Vulnerability of the Indian coastal region to damage from sea level rise. Curr Sci 59(3):152–156
Singh A, Panda SN, Saxena CK, Verma CL, Uzokwe VN, Krause P, Gupta SK (2016) Optimization modeling for conjunctive use planning of surface water and groundwater for irrigation. J Irrig Drain Eng 142(3):04015060. https://doi.org/10.1061/(asce)ir.1943-4774.0000977
Singh AK, Jasrotia AS, Taloor AK, Kotlia BS, Kumar V, Roy S, Ray PKC, SinghKK SAK, Sharma AK (2017) Estimation of quantitative measures of total water storage variation from GRACE and GLDAS-NOAH satellites using geospatial technology. Quatern Int 444:191–200
Singh AK, Kotlia BS, Singh KK, Kumar A (2019a) Monitoring groundwater fluctuations over India during Indian summer monsoon (ISM) and Northeast monsoon using GRACE satellite: impact on agriculture. Quat Int 507:342–351
Singh DD, Thind PS, Sharma M, Sahoo S, John S (2019b) Environmentally sensitive elements in groundwater of an industrial town in India: Spatial distribution and human health risk. Water 11(11):2350
Singh AK, Tripathi JN, Taloor AK, Kotlia BS, Singh KK, Attri SD (2021) Seasonal ground water fluctuation monitoring using grace satellite technology over Punjab and Haryana during 2005–2015. In: Taloor AK, Kotlia BS, Kumar K (eds) Water, cryosphere, and climate change in the Himalayas: a geospatial approach. Springer, Cham, pp 161–170
Sinha D, Syed TH, Famiglietti JS, Reager JT, Thomas RC (2017) Characterizing drought in India using GRACE observations of terrestrial water storage deficit. J Hydrometeorol 18(2):381–396
Small EE (2005) Climatic controls on diffuse groundwater recharge in semiarid environments of the southwestern United States. Water Resour Res 41(4):W04012
Small C, Nicholls RJ (2003) A global analysis of human settlement in coastal zones. J Coastal Res 19(3):584–599
Solomon S, Manning M, Marquis M, Qin D (2007) Climate change 2007-the physical science basis: working group I contribution to the fourth assessment report of the IPCC, vol 4. Cambridge University Press
Soni A, Syed TH (2015) Diagnosing land water storage variations in major Indian river basins using GRACE observations. Glob Planet Ch 133:263–271
Sood V, Singh S, Taloor AK, Prashar S, Kaur R (2020) Monitoring and mapping of snow cover variability using topographically derived NDSI model over north Indian Himalayas during the period 2008–19. Appl Comput Geosci 8:100040
Sood V, Gupta S, Gusain HS, Singh S, Taloor AK (2021a) Topographic controls on subpixel change detection in western Himalayas. Remote Sens Appl Soc Environ 21:100465
Sood V, Gusain HS, Gupta S, Taloor AK, Singh S (2021b) Detection of snow/ice cover changes using subpixel-based change detection approach over Chhota-Shigri glacier, Western Himalaya, India. Quat Int 575:204–212
Spalding RF, Exner ME (1993) Occurrence of nitrate in groundwater—a review. J Environ Qual 22(3):392–402
Stuart ME, Gooddy DC, Bloomfield JP, Williams AT (2011) A review of the impact of climate change on future nitrate concentrations in groundwater of the UK. Sci Total Environ 409(15):2859–2873
Sudhakar A, Narsimha A (2013) Suitability and assessment of groundwater for irrigation purpose: a case study of Kushaiguda area, Ranga Reddy district, Andhra Pradesh India. Adv Appl Sci Res 4(6):75–81
Sukhija BS (2008) Adaptation to climate change: strategies for sustaining groundwater resources during droughts. Geol Soc Lond Spec Publ 288(1):169–181
Sultana Z, Coulibaly P (2011) Distributed modelling of future changes in hydrological processes of Spencer Creek watershed. Hydrol Process 25(8):1254–1270
Sun AY, Scanlon BR, Zhang Z, Walling D, Bhanja SN, Mukherjee A, Zhong Z (2019) Combining physically based modeling and deep learning for fusing GRACE satellite data: Can we learn from mismatch? Water Resour Res 55(2):1179–1195
Suthar S, Bishnoi P, Singh S, Mutiyar PK, Nema AK, Patil NS (2009) Nitrate contamination in groundwater of some rural areas of Rajasthan India. J Hazard Mater 171(1–3):189–199
Swain S, Mishra SK, Pandey A (2020a) Assessment of meteorological droughts over Hoshangabad district, India. In: IOP conference series: earth and environmental science, IOP Publishing, 491(1):012012. https://doi.org/10.1088/1755-1315/491/1/012012
Swain S, Sharma I, Mishra SK, Pandey A, Amrit K, Nikam V (2020b) A framework for managing irrigation water requirements under climatic uncertainties over Beed district, Maharashtra, India. In: World environmental and water resources congress 2020b: water resources planning and management and irrigation and drainage, VA: ASCE, Reston, pp 1–8. https://doi.org/10.1061/9780784482957.001
Swain S, Mishra SK, Pandey A (2021a) A detailed assessment of meteorological drought characteristics using simplified rainfall index over Narmada River Basin India. Environ Earth Sci 80:221. https://doi.org/10.1007/s12665-021-09523-8
Swain S, Mishra SK, Pandey A, Dayal D (2021b) Identification of meteorological extreme years over central division of Odisha using an index-based approach. In: Hydrological extremes, Springer, Cham, pp 161–174. https://doi.org/10.1007/978-3-030-59148-9_12
Swain S, Mishra SK, Pandey A, Dayal D (2022a) Spatiotemporal assessment of precipitation variability, seasonality, and extreme characteristics over a Himalayan catchment. Theoret Appl Climatol 147(1):817–833. https://doi.org/10.1007/s00704-021-03861-0
Swain S, Mishra SK, Pandey A, Kalura P (2022b) Inclusion of groundwater and socio-economic factors for assessing comprehensive drought vulnerability over Narmada River Basin, India: a geospatial approach. Appl Water Sci 12:14. https://doi.org/10.1007/s13201-021-01529-8

Swain S, Sahoo S, Taloor AK (2022c) Groundwater quality assessment using geospatial and statistical approaches over Faridabad and Gurgaon districts of National Capital Region. India. Appl Water Sci 12:75. https://doi.org/10.1007/s13201-022-01604-8

Swapna P, Ravichandran M, Nidheesh G, Jyoti J, Sandeep N, Deepa JS, Unnikrishnan AS (2020) Sea-level rise. In: Krishnan R, Sanjay J, Gnanaseelan C, Mujumdar M, Kulkarni A, Chakraborty S (eds) Assessment of climate change over the Indian region. Springer, Singapore, pp 175–189

Tague C, Grant GE (2009) Groundwater dynamics mediate low-flow response to global warming in snow-dominated alpine regions. Water Resour Res 45(7):W07421

Takal JK, Quaye-Ballard JA (2018) Bacteriological contamination of groundwater in relation to septic tanks location in Ashanti Region Ghana. Cogent Environ Sci 4(1):1556197

Taloor AK, Pir RA, Adimalla N, Ali S, Manhas DS, Roy S, Singh AK (2020) Spring water quality and discharge assessment in the Basantar watershed of Jammu Himalaya using geographic information system (GIS) and water quality Index (WQI). Groundw Sustain Dev 10:100364

Taloor AK, Manhas DS, Kothyari GC (2021) Retrieval of land surface temperature, normalized difference moisture index, normalized difference water index of the Ravi basin using Landsat data. Appl Comput Geosci 9:100051

Taniguchi M (ed) (2011) Groundwater and subsurface environments: human impacts in Asian coastal cities. Springer Science & Business Media, Germany

Taylor RG, Koussis AD, Tindimugaya C (2009) Groundwater and climate in Africa—a review. Hydrol Sci J 54(4):655–664

Taylor RG, Scanlon B, Döll P, Rodell M, Van Beek R, Wada Y, Longuevergne L, Leblanc M, Famiglietti JS, Edmunds M, Konikow L (2013a) Ground water and climate change. Nat Clim Chang 3(4):322–329

Taylor RG, Todd MC, Kongola L, Maurice L, Nahozya E, Sanga H, MacDonald AM (2013b) Evidence of the dependence of groundwater resources on extreme rainfall in East Africa. Nat Clim Chang 3(4):374–378

Tiwari AK, Pal DB (2021) Recent trends in groundwater conservation and management. In: Madhav S, Singh P (eds) Groundwater geochemistry: pollution and remediation methods. John Wiley & Sons Ltd, New York, pp 379–391

Tiwari VM, Wahr J, Swenson S (2009) Dwindling groundwater resources in northern India, from satellite gravity observations. Geophys Res Lett 36:L18401

Tomar M (1999) Quality assessment of water and wastewater. CRC Press, Florida

Treidel H, Martin-Bordes JL, Gurdak JJ (eds) (2011) Climate change effects on groundwater resources: a global synthesis of findings and recommendations. CRC Press, Florida

Unnikrishnan AS, Nidheesh AG, Lengaigne M (2015) Sea-level-rise trends off the Indian coasts during the last two decades. Curr Sci 108(5):966–971

Van Geen A, Zheng Y, Goodbred S Jr, Horneman A, Aziz Z, Cheng Z, Stute M, Mailloux B, Weinman B, Hoque MA, Seddique AA (2008) Flushing history as a hydrogeological control on the regional distribution of arsenic in shallow groundwater of the Bengal Basin. Environ Sci Technol 42(7):2283–2288

Villar PC, Ribeiro WC (2011) The Agreement on the Guarani Aquifer: a new paradigm for transboundary groundwater management? Water Int 36(5):646–660

Vissa NK, Anandh PC, Behera MM, Mishra S (2019) ENSO-induced groundwater changes in India derived from GRACE and GLDAS. J Earth Syst Sci 128(5):115

Wada Y, Van Beek LP, Van Kempen CM, Reckman JW, Vasak S, Bierkens MF (2010) Global depletion of groundwater resources. Geophys Res Lett 37(20):L20402

Wada Y, van Beek LP, Sperna Weiland FC, Chao BF, Wu YH, Bierkens MF (2012) Past and future contribution of global groundwater depletion to sea-level rise. Geophys Res Lett 39(9):L09402

WHO (2004) Guidelines for drinking-water quality: recommendations. World Health Organization, Geneva

Wrathall DJ, Mueller V, Clark PU, Bell A, Oppenheimer M, Hauer M, Kulp S, Gilmore E, Adams H, Kopp R, Abel K, Call M, Chen J, deSherbinin A, Fussell E, Hay C, Jones B, Magliocca N, Marino E, Slangen A, Warner K (2019) Meeting the looming policy challenge of sea-level change and human migration. Nat Clim Chang 9(12):898–901

Xie H, Longuevergne L, Ringler C, Scanlon BR (2020) Integrating groundwater irrigation into hydrological simulation of India: case of improving model representation of anthropogenic water use impact using GRACE. J Hydrol Reg Stud 29:100681

Xu P, Feng W, Qian H, Zhang Q (2019) Hydrogeochemical characterization and irrigation quality assessment of shallow groundwater in the Central-Western Guanzhong Basin, China. Int J Environ Res Public Health 16(9):1492

Yadav B, Gupta PK, Patidar N, Himanshu SK (2020) Ensemble modelling framework for groundwater level prediction in urban areas of India. Sci Total Environ 712:135539

Yahaya A, Adegbe AA, Emurotu JE (2012) Assessment of heavy metal content in the surface water of Oke-Afa Canal Isolo Lagos Nigeria. Arch of App Sci Res 4(6):2322–2326

Yakirevich A, Melloul A, Sorek S, Shaath S, Borisov V (1998) Simulation of seawater intrusion into the Khan Yunis area of the Gaza Strip coastal aquifer. Hydrogeol J 6(4):549–559

Zaveri E, Grogan DS, Fisher-Vanden K, Frolking S, Lammers RB, Wrenn DH, Prusevich A, Nicholas RE (2016) Invisible water, visible impact: groundwater use and Indian agriculture under climate change. Environ Res Lett 11(8):084005

Zhang Q, Xu P, Qian H (2019) Assessment of groundwater quality and human health risk (HHR) evaluation of nitrate in the Central-Western Guanzhong Basin, China. Int J Environ Res Public Health 16(21):4246

Zhang Q, Xu P, Qian H (2020a) Groundwater quality assessment using improved water quality index (WQI) and human health risk (HHR) evaluation in a semi-arid region of northwest China. Expo Health 12:487–500

Zhang Q, Xu P, Qian H, Yang F (2020b) Hydrogeochemistry and fluoride contamination in Jiaokou Irrigation District, Central China: assessment based on multivariate statistical approach and human health risk. Sci Total Environ 741:140460

Zhang Q, Qian H, Xu P, Li W, Feng W, Liu R (2021a) Effect of hydrogeological conditions on groundwater nitrate pollution and human health risk assessment of nitrate in Jiaokou Irrigation District. J Clean Prod 298:126783

Zhang Q, Xu P, Chen J, Qian H, Qu W, Liu R (2021b) Evaluation of groundwater quality using an integrated approach of set pair analysis and variable fuzzy improved model with binary semantic analysis: a case study in Jiaokou Irrigation District, east of Guanzhong Basin China. Sci Total Environ 767:145247

Zhu Y, Fox RH (2003) Corn–soybean rotation effects on nitrate leaching. Agron J 95(4):1028–1033