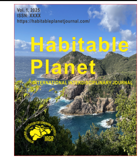
Habitable Planet, 2025, 1(1&2):249–270

Habitable Planet

Journal Homepage: www.habitableplanetjournal.com



Groundwater potential and sustainability in the Indian subcontinent

E. Shaji*[1], M. Santosh[2,3], K.V. Sarath[1], P.K. Krishnaprasad[1], G. Indu[1], and S.G. Dhanil Dev[1]

[1] *Department of Geology, University of Kerala, Kariavattom Campus, Trivandrum 695581, Kerala, India*
[2] *School of Earth Sciences and Resources, China University of Geosciences (Beijing), 29 Xueyuan Road, Beijing 100083, China*
[3] *Faculty of Science, Kochi University, Kochi 780-8520, Japan*

ABSTRACT

Understanding regional groundwater characteristics is an important aspect for sustainability. The Indian subcontinent is one of the critical regions because of the high population and rapid developmental activities where the groundwater potential plays a crucial role in meeting the water demands for agriculture, domestic, and industrial purposes. Here we evaluate the characteristics of the major aquifer systems in the Indian subcontinent and divide these into three distinct types viz. sedimentary aquifers comprising ∼48%, followed by metamorphic crystalline aquifers ∼32% and igneous crystalline aquifers at ∼20%. In 2024, India extracted 245.64 BCM of groundwater through all these aquifers, representing approximately 60.47% of the nation's annual extractable groundwater resource (406.19 BCM), as assessed by the Central Ground Water Board with a total annual recharge of 446.90 BCM. Out of 6,746 groundwater assessment blocks in India, 751 are over-exploited, where extraction exceeds annual recharge, 127 are saline due to saline groundwater in phreatic aquifers, and 4,951 are classified as safe. Severe over-exploitation of groundwater is observed in sedimentary aquifers of the Indo-Gangetic alluvial system, notably in Haryana, Punjab, Rajasthan, and Delhi, whereas significant over-exploitation in metamorphic crystalline aquifers is reported of Tamil Nadu and Karnataka, particularly in cities such as Bangalore and Chennai. Nevertheless, most assessment units are categorized as 'safe,' offering ample opportunity for sustainable groundwater development. Our review shows that ∼67% of India's groundwater is extracted annually primarily for irrigation. We observe substantial disparities in the distribution and extraction of groundwater for irrigation across the country, exacerbated by increasing water shortages linked to rising temperatures. These findings emphasize the urgent need for building efficient irrigation systems in mitigating climate-induced threats. Therefore, to align with UN Sustainable Development Goals (SDG -6,13 and 15) and safeguard India's productive aquifer units, it is essential to implement managed aquifer recharge schemes across the country.

ARTICLE INFO

History:
Received Aug 01, 2025
Revised Sep 06, 2025
Accepted Sep 06, 2025

Keywords:
Groundwater
Sustainable development goals
Aquifers of India
Groundwater recharge
Indo-Gangetic alluvium

Citation:
Shaji, E., Santosh, M., Sarath, K.V., Krishnaprasad, P.K., Indu, G., Dhanil Dev, S.G., 2025. Groundwater potential and sustainability in the Indian subcontinent. Habitable Planet 1(1&2), 249–270. https://doi.org/10.63335/j.hp.2025.0019.

*Corresponding author. Email: shajigeology@keralauniversity.ac.in, shajigeology@gmail.com (ES)

Research highlights

- The aquifers of Indian subcontinent are classified into sedimentary (∼48%), metamorphic crystalline (∼32%), and igneous crystalline (∼20%) systems.
- In 2024, 245.64 BCM of groundwater was extracted, accounting for 60.47% of India's annual extractable resource.
- Over-exploitation is concentrated in the Indo-Gangetic sedimentary belt and crystalline aquifers of Tamil Nadu and Karnataka.
- Irrigation accounts for ∼67% of groundwater use, stressing the need for efficient systems and managed aquifer recharge to ensure sustainability.

1 Introduction

Although Planet Earth is made up of 70% water, only 3% of Earth's water is freshwater and of which only 30% is groundwater. Safe and affordable drinking water, improving water quality and reducing pollution, implementation of integrated water resource management are among the various aspects related to water under United Nations' Sustainable Development Goals. Thus, understanding regional groundwater characteristics is highly significant for sustainability. In this context, the Indian subcontinent is one of the critical regions because of the high population and rapid developmental activities. Groundwater potential in this region plays a crucial role in meeting the country's water demands for agriculture, domestic, and industrial purposes. India is one of the largest users of groundwater globally, with around 85% of rural drinking water supply and 65% of irrigation water sourced from groundwater (Singh and Singh, 2002; Siebert et al., 2010; Saha and Ray, 2018; Shaji et al., 2024). The geological framework of India, comprising complex lithologies and structures developed through multiple orogenic cycles, and different types of aquifers, has given rise to diverse groundwater potential (Mukherjee et al., 2012; Mukherjee et al., 2015; Saha and Ray, 2018; Das, 2023; Scanlon et al., 2023). Gupta and Sharma (2023) comprehensively reviewed groundwater–surface water interaction studies in India, highlighting a predominant focus on the Ganga river basin, limited regional coverage in western and central India, and the widespread use of isotopic, hydrochemical, and hydrological methods, while also emphasizing the lack of adequate institutional recognition of such interactions. The presence of alluvial plains, sedimentary basins, and fractured rock formations enhances the groundwater storage capacity across the country (Rodell et al., 2009; Dangar et al., 2021; Shaji et al., 2021; Sahoo et al., 2025). One of the key factors influencing groundwater potential is the monsoon pattern. India experiences a diverse monsoon climate, with different regions receiving varying amounts of rainfall (Lal, 2003; Pattanaik and Rajeevan, 2010; Guhathakurta et al., 2015). This rainfall recharges aquifers, replenishing groundwater reserves. However, over-exploitation and inadequate recharge mechanisms in certain areas have led to declining groundwater levels and quality issues in some regions (CGWB, 2023).

Rainfall in India exhibits significant spatial and temporal variations, with over 75% of annual rainfall occurring during the monsoon months from June to September. This leads to considerable differences in rainfall patterns across the country, with regions such as the Western Ghats and Meghalaya Hills receiving heavy rainfall exceeding 250 cm annually, whereas areas like Northern Kashmir and Western Rajasthan receive less than 40 cm. Swain et al. (2022) provided a comprehensive review on the impact of climate change on groundwater hydrology in India, emphasizing the region-specific vulnerabilities of aquifer systems and highlighting the urgent need for adaptive groundwater management strategies under changing climatic conditions.

Studies conducted by various workers (Singh and Singh, 2002; Mukherjee et al., 2015; Saha and Ray, 2018; Nair and Indu, 2021; Dey et al., 2024; Saha et al., 2024; Taloor et al., 2024; Sahoo et al., 2025) and organizations such as the Central Ground Water Board (CGWB), various state groundwater departments and research institutions have provided valuable insights into India's groundwater potential, status, and threats. These studies utilize hydrogeological mapping, aquifer characterization, and groundwater modeling techniques to assess groundwater availability and sustainability. The National Aquifer Mapping and Management Program (NAQUIM) initiated by the Government of India aims to assess and manage groundwater resources efficiently. It involves mapping aquifer systems across the country and implementing measures for sustainable groundwater management. Additionally, advancements in remote sensing and Geographic Information System (GIS) technologies have facilitated the assessment and monitoring of groundwater resources on a regional scale. Similarly, groundwater storage studies were carried out based on satellite observations of the time-varying Earth's gravitational field from the Gravity Recovery and Climate Experiments (GRACE) (Panda et al., 2021; Singh et al., 2023).

A pragmatic evaluation of groundwater resource conditions, considering renewable groundwater resources stemming from recharge, withdrawals, and natural discharge, is imperative for informed groundwater management decisions, particularly in regions grappling with groundwater challenges. India, with its reliance on dynamic groundwater resources primarily fuelled by annual precipitation, stands as a prominent example. Official estimates India's annual extractable groundwater resource is 406.19 billion cubic meters (BCM) as per data from the Central Ground Water Board (CGWB, 2024).

In this paper, we present a comprehensive overview of India's groundwater potential, envisioning a future trajectory guided by sustainable management practices and innovative solutions.

2 Major aquifer systems in India

As per CGWB (2023, 2024) and other published data (Mukherjee et al., 2012, 2015; Saha and Ray, 2018; Dey et al., 2024; Saha et al., 2024; Taloor et al., 2024; Sahoo et al., 2025) the major Indian aquifers can be divided in to fourteen systems: (1) basaltic aquifer, (2) granitic aquifer, (3) mafic and ultramafic aquifers, (4) schist aquifer, (5) quartzite aquifer, (6) khondalite (granulite facies metapelites) aquifer, (7) gneissic aquifer, (8) charnockite (orthopyroxene-bearing granulite) aquifer, (9) banded gneissic aquifer, (10) laterite aquifer, (11) sandstone aquifer, (12) alluvium aquifer, (13) shale aquifer, and (14) limestone aquifer (CGWB, 2023, 2024) (Fig. 1). In this study, we propose a more integrated and simplified classification based on lithologic association as: (1) sedimentary aquifers comprising ∼48%, (2) metamorphic crystalline aquifers ∼32% and (3) Igneous crystalline aquifers at ∼20%. In the following sections, the details of these aquifer systems are evaluated.

2.1 Sedimentary aquifers (Fig. 2)

Sedimentary aquifers, which constitute around 48% of the total, are the major aquifers of the Indian subcontinent. The sedimentary aquifers are divided into four and its hydrogeological characteristics are given below.

2.1.1 Alluvial aquifer system

India's alluvial aquifer system covers ∼30% of the country's land area, or 945723 km^2, which includes the major Indo Gangetic alluvium (CGWB, 2023) (Fig. 2). The alluvial aquifer system in the country is divided into six categories: younger alluvium (∼36%), older alluvium (∼43%), aeolian alluvium (∼16%), coastal alluvium (∼4%), valley fills (0.6%), and pebble & gravel (0.4%). The total area of younger alluvium in India is 339298 km^2. Bihar has the younger alluvium (73971 km^2), followed by Assam (52391 km^2), West Bengal (51464 km^2) and Chhattisgarh, Karnataka, Kerala, Meghalaya, Nagaland, and Tripura also have younger alluvium. The total extent of older alluvium is 407490 km^2. Uttar Pradesh has maximum (172526 km^2) of older alluvium, followed by Rajasthan (80114 km^2) and Haryana (28855 km^2) and Gujarat (25106 km^2). 98% of the Haryana State is occupied by the alluvial deposits.

The aeolian alluvium in India (149208 km^2) is distributed in Rajasthan (114989 km^2) followed by Haryana (12766 km^2), Gujarat (8948 km^2) and Jammu and Kashmir (2816 km^2). The total area of coastal alluvium in the country is 40660 km^2. Gujarat consist of 19048 km^2 coastal alluvium followed by Andhra Pradesh (6920 km^2), Tamil Nadu (5845 km^2) and Orissa (5405 km^2). Around 3864 km^2 consist of valley fills of which Gujarat has 2309 km^2 of valley fills followed by Himachal Pradesh (650 km^2), West Bengal (571) and Punjab (335 km^2). Similarly, 5203 km^2 area is covered by of pebble and gravel aquifers, Uttar Pradesh consists of 1960 km^2 of pebble and gravel aquifer followed by Uttarakhand (1247 km^2) and Jharkhand (513 km^2).

The Quaternary sediments of the Bay of Bengal's Coastal Alluvium, Aeolian Alluvium (Silt/Sand), Older Alluvium, and Recent Alluvium are primarily significant unconsolidated formations that make up the main alluvial aquifers. The main constituents of these sediments are clays, silts, and sands, pebble and Kankar, etc. These are, without a doubt, the most important groundwater reserves for extensive and large-scale development. The Indus-Ganga-Brahmaputra basin's hydrogeological conditions and groundwater regime suggest the presence of prospective aquifers with sizable freshwater reserves. These groundwater reservoirs, which receive a lot of rainfall and buried beneath a thick layer of permeable sediments, are heavily utilised and refilled annually. These areas have a massive groundwater reserve in the deeper part below the zone of fluctuation as well as in the deeper confined aquifers (CGWB, 2022).

The aquifers of north-western and north-eastern Indian states mainly consist of alluvium, which include Jammu and Kashmir, Himachal Pradesh, Punjab, Haryana, Uttar Pradesh, Uttarakhand, Gujarat, Rajasthan, West Bengal, Tripura, Nagaland, Meghalaya, Manipur, and Assam. Smaller segments of southern Indian states also cover alluvium aquifers especially in the coastal region.

The Indo-Gangetic belt is the world's largest expanse of thick alluvium, formed by the deposition of silt by numerous rivers. These highly potential alluvial plains are one of the world's most intensively farmed/irrigated regions. The main crops grown are rice and wheat, which are rotated. Maize, sugarcane, and cotton are some of the region's other important crops. The Indo-Gangetic plains are among the

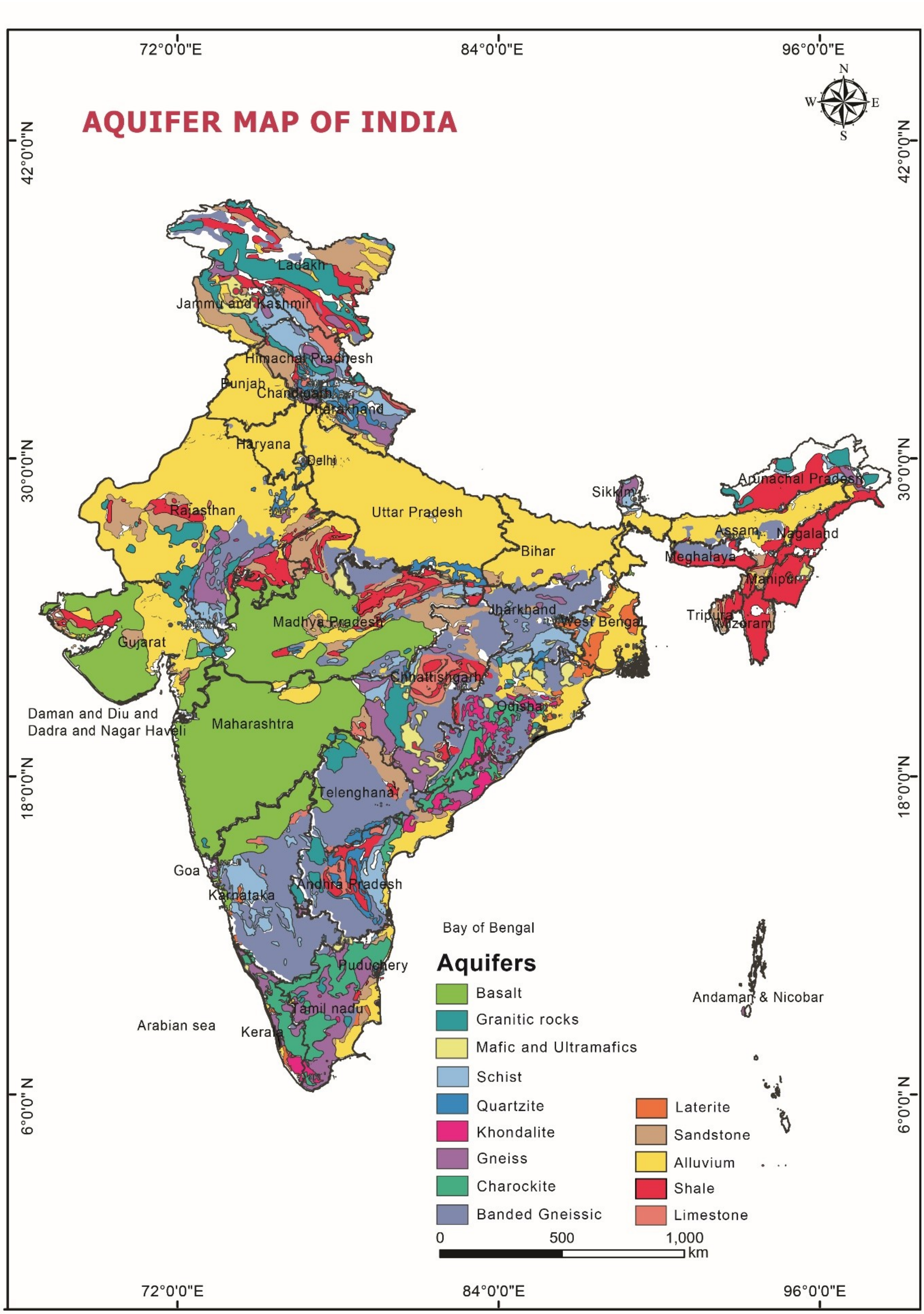


Fig. 1. India's major aquifer systems are classified into 14 distinct units based on their lithological characteristics (modified after CGWB, 2012, 2023, 2024).

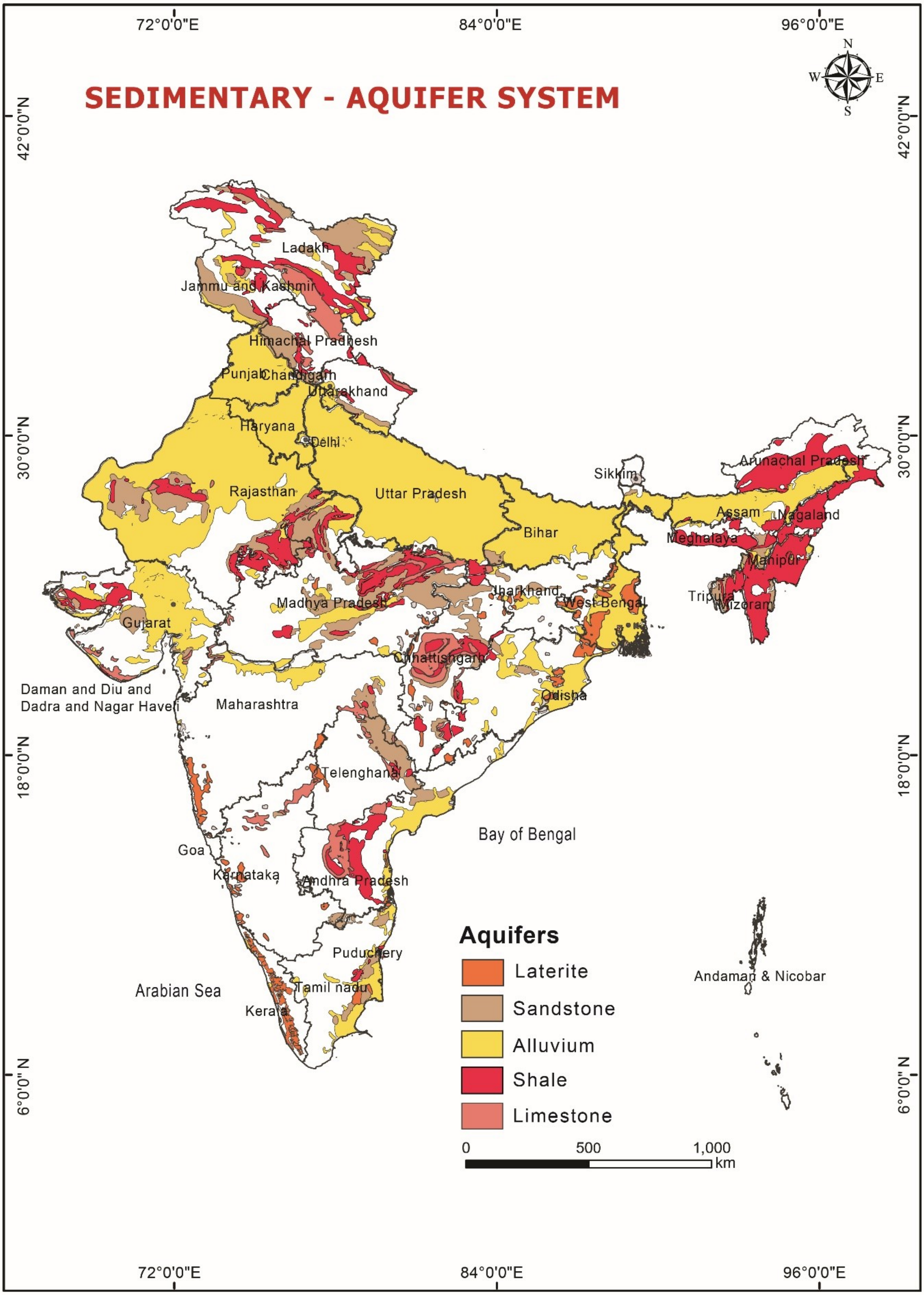


Fig. 2. Sedimentary aquifers, the major aquifers of the Indian subcontinent, are divided into four units (modified after CGWB, 2012, 2023).

world's most densely populated regions. The Indus-Ganga plains, also known as the "Great Plains," are vast floodplains between the Indus and Ganga-Brahmaputra river systems. They run parallel to the Himalaya Mountains, from Jammu and Kashmir in the west to Assam in the east, and drain the majority of northern and eastern India. The Indo-Gangetic plain is traversed mainly by three major rivers: the Ganges, Indus, and Brahmaputra.

2.1.2 Sandstone aquifer system

The majority of the sandstone aquifers are Carboniferous to Mio-Pliocene in age. This category includes the Tertiary deposits along the west and east coasts of the peninsula as well as the terrestrial freshwater deposits that are part of the Gondwana System. Locally, the Gondwana sandstones create extremely promising aquifers. They have mediocre potential elsewhere, and they produce little where they are. The most widespread and productive aquifers in this category are the Gondwanas, Lathis, Tipams, Cuddalore sandstones, and their equivalents.

India's sandstone aquifer system covers 8.21% of the country's land area, or 260415.61 km^2 (CGWB, 2023) (Fig. 2). The sandstone aquifer system in this country is divided into four categories: sandstone-conglomerate (41%), sand stone with shale (36%), sandstone with coal beds (15%), sandstone with clay (8%). The total area of sandstone-conglomerate in India is 106380 km^2. Jammu and Kahmir cover largest sandstone-conglomerate aquifer (106380 km^2) among India's 28 states, followed by Himachal Pradesh (7500 km^2). and Andhra Pradesh (6525 km^2). The total area of sandstone-shale aquifer is 94775 km^2. Rajasthan consists of 23,874 km^2 of sandstone-shale aquifer followed by Madhya Pradesh has (19102 km^2) Jammu and Kashmir (18029 km^2) and Chhattisgarh (11642 km^2) and Gujarat (25106 km^2). The total area of sandstone with coal beds in India is (37720 km^2). Chhattisgarh has 8766 km^2 of sandstone with coal beds followed by Jammu and Kashmir (8392 km^2), and Manipur (4712 km^2). The total area of Sandstone with clay in the country is (21540 km^2). Andhra Pradesh consists of (10851 km^2) Sandstone with clay followed by Tamil Nadu (4739 km^2), Jammu and Kashmir (1859 km^2). The Mio-Pliocene sedimentary formation occurs along Kerala coast has potential sandstone aquifers.

The hydrogeology of the sandstone consists of single and multiple aquifer systems as unconfined to confined respectively. The lowest aquifer thickness of sandstone aquifer was observed from Karnataka (60–80 m), and Andhra Pradesh (20–150 m) and maximum from Assam and Jharkhand (up to 600 m), followed by Bihar, Chhattisgarh, Gujarat, Madhya Pradesh, and Maharashtra (up to 400 m). The fractures in sandstone aquifer encountered maximum depth from Himachal Pradesh (1600 m), and lowest from Andhra Pradesh (100 m). Transmissivity (m^2/day) in the sandstone aquifer is highest in Tamil Nadu (500–6000), and the lowest in Jammu and Kashmir (3–5). The highest yield (m^3/day) observed from Tamil Nadu (860–4800) and Himachal Pradesh (20–3662) and the lowest yield from Assam (5–100).

2.1.3 Shale aquifer system

India's shale aquifer system covers 7.12% of the country's land area, or 225397.03 km^2 (CGWB, 2023) (Fig. 2). The shale aquifer system in this country is divided into four categories: shale with limestone (11%), shale with sandstone (64%), shale, limestone with sandstone (22%), and shale (3%). The total area of shale with limestone is 21884 km^2. Chhattisgarh has largest shale with limestone aquifer (9411 km^2) among India's 28 states, followed by Rajasthan (3349 km^2). and Jammu and Kashmir (2727 km^2). The total area of shale with sandstone aquifer is 151729 km^2. Arunachal Pradesh has 23,801 km^2 of shale with sandstone aquifer followed by Madhya Pradesh (22477 km^2), Andhra Pradesh (18029 km^2) and Rajasthan (12127 km^2) and Gujarat (25106 km^2). The total area of shale, limestone and sandstone is 45399 km^2. Jammu and Kashmir consist of 22032 km^2 of shale, limestone and sandstone aquifer followed by Arunachal Pradesh (11761 km^2), and Meghalaya (4536 km^2). The total area of shale aquifer is 5938 km^2 and Gujarat consist of 3479 km^2 followed by Himachal Pradesh (1051 km^2), and Mahya Pradesh (872 km^2).

The shale aquifer consists of single aquifer system, with unconfined to confined aquifer type. The lowest aquifer thickness of shale aquifer was observed from Himachal Pradesh and Karnataka (40–150 m), and the maximum from Rajasthan, Maharashtra, Madhya Pradesh, and Chhattisgarh (up to 450 m). The fractures in shale aquifers show varying maximum depth such as highest in Himachal Pradesh (190 m), and lowest from Jharkhand (75 m). Transmissivity (m^2/day) in the shale aquifer is highest in Chhattisgarh (450), and the lowest in Andhra Pradesh and Karnataka (1.2–24). The highest yield was observed from Tamil Nadu (20–2100 m^2/day) and Chhattisgarh (9–1728) and the lowest from Uttarakhand and Gujarat (200).

2.1.4 Limestone aquifer system

Marble, dolomite, and limestone are examples of carbonate rocks that are part of the consolidated sedimentary rocks. Limestones are the most abundant type of carbonate rock. The principal zones of water bearing in carbonate rocks are the solution cavities and fractures. Separated from other major litho-units like conglomerates, sandstones, shales, slates, and quartzites, limestones and dolomites make up the consolidated sedimentary rocks of the Cuddapah and Vindhyan subgroups and their equivalents.

India's limestone aquifer system covers 1.98% of the country's land area, or 62898.91 km^2 (CGWB, 2023) (Fig. 2). The limestone aquifer system in this country is divided into four categories: Miliolitic limestone (4.7%), limestone/dolomite (86.3%), lime stone with shale (8.6%), and marble (1.6%). The total area of miliolitic limestone in India is 2946 km^2. Gujarat has the largest miliolitic limestone aquifer (2943 km^2) among India's 28 states, followed by Rajasthan (3 km^2). The total amount of limestone/dolomite aquifer is 54306 km^2. Chhattisgarh (13122 km^2) has the largest extent of limestone/dolomite followed by Jammu and Kashmir (10399 km^2), Andhra Pradesh (8613 km^2), Karnataka (5872 km^2), Himachal Pradesh has (5510 km^2), and Uttarakhand (1457 km^2). The total area of limestone with shale in India is 5414 km^2. Chhattisgarh leads (2133 km^2) for limestone with shale aquifer followed by Andhra Pradesh (1721 km^2), and Maharashtra (1376 km^2). The total area of marble aquifer in the country is 996 km^2 with Maharashtra (356 km^2) Rajasthan (277 km^2), Gujarat (175 km^2) hosting most of these.

The hydrogeology of the limestone aquifer consists of mainly single aquifer system, with confined, unconfined to semi-confined aquifer type. The lowest aquifer thickness of limestone aquifer was observed from Himachal Pradesh and Karnataka (40–150 m), and the maximum from Rajasthan, Maharashtra, Madhya Pradesh, and Chhattisgarh (up to 450 m). The fractures in limestone aquifer encountered maximum depth from Andhra Pradesh (190 m), and lowest from Maharashtra (15 m). Transmissivity (m^2/day) in the limestone aquifer is highest in Andhra Pradesh (740), and the lowest in Assam (10–172). The highest yield (m^3/day) observed from Andhra Pradesh (20–2100) and the lowest yield from Uttarakhand (20–200).

2.1.5 Lateritic aquifer system

Laterites are formed through the chemical weathering of sedimentary rocks like sandstones, clays, and limestones, metamorphic rocks such as gneisses, migmatites, and granites, and igneous rocks like basalts, gabbros, and peridotites. Lateritization occurs in hot, humid tropical regions and is rich in iron and aluminium. The most widely distributed and well-developed aquifer is laterite, particularly in the peninsular states. Where the saturated zone is thicker, laterite forms potential aquifers along valleys and topographic lows that can support large diameter open wells for irrigation and residential use.

According to CGWB reports, India's lateritic aquifer system covers 1% of the country's land area, or 40926 km^2 (Fig. 2). Only 12 states in India were noticed lateritic aquifer in the country and the West Bengal (14280 km^2) covers the largest lateritic aquifer in India among India's 28 states, followed by Maharashtra (5516 km^2), Orissa (5305 km^2) etc. In the mid land region of Kerala, laterite is a major aquifer unit.

The hydrogeology of the lateritic aquifer consists of mainly single aquifer system, with unconfined aquifer type. The weathered thickness of khondalite aquifer was observed from (2–40 m) and the groundwater zone in lateritic aquifer encountered in different depths within the 40 m. Transmissivity (m^2/day) in the lateritic aquifer is highest in Andhra Pradesh (1500), and the lowest in Orissa (nearly 20). The highest yield (m^3/day) observed from Chhattisgarh (6048).

2.2 Metamorphic crystalline aquifers

These aquifers represent the second largest unit in India in terms of its area representation (∼32%). Metamorphic crystalline aquifers are represented by six distinct rocks types and they represent phreatic, semi-confined, and confined aquifers. In general, they have low porosity and permeability due to the compact and crystalline nature of the rock matrix. These aquifers often exhibit limited primary porosity, relying instead on secondary porosity features such as fractures, joints, and faults for groundwater storage and flow. Water yield from crystalline aquifers tends to be variable and influenced by the spatial distribution and effective porosity of the entire aquifer units. Additionally, groundwater in crystalline aquifers may exhibit higher mineralization levels compared to other aquifer types due to prolonged interaction with the rock matrix.

In these terrains, groundwater is typically found under phreatic conditions in the mantle of weathered rock, overlying the crystalline rock. Within the fissures, fractures, cracks, and joints exist within the crystalline rock, groundwater occurs in a semi-confined or confined state. In comparison to the volume of water stored under semi-confined conditions within the crystalline rock, the storage in the overlying phreatic aquifer is often significantly greater. In such scenarios, the network of fissures and fractures acts as permeable conduits, facilitating the flow of water to bore wells. They mostly occur in states like Arunachal Pradesh, Madhya Pradesh, Goa, Kerala, Karnataka, Tamil Nadu Telangana, Andhra Pradesh, Orissa, Chhattisgarh, and Jharkhand (Fig. 3). The six subdivisions of metamorphic aquifers are described below.

2.2.1 Banded Gneissic Complex (BGC) aquifer System

The north-western and north-eastern Indian states mainly consist banded gneissic aquifers in India and which include Karnataka, Andhra Pradesh, Telangana, Chhattisgarh, Orissa, Madhya Pradesh, Jharkhand, Tamil Nadu. Southern Indian states mainly cover banded gneissic aquifers (Fig. 3). According to CGWB reports, India's banded gneissic aquifer system covers 15% of the country's land area, or 478383 km^2 (CGWB, 2023). Karnataka is the wide spread banded gneissic aquifer in the country (114943), followed by Andhra Pradesh (110284 km^2).

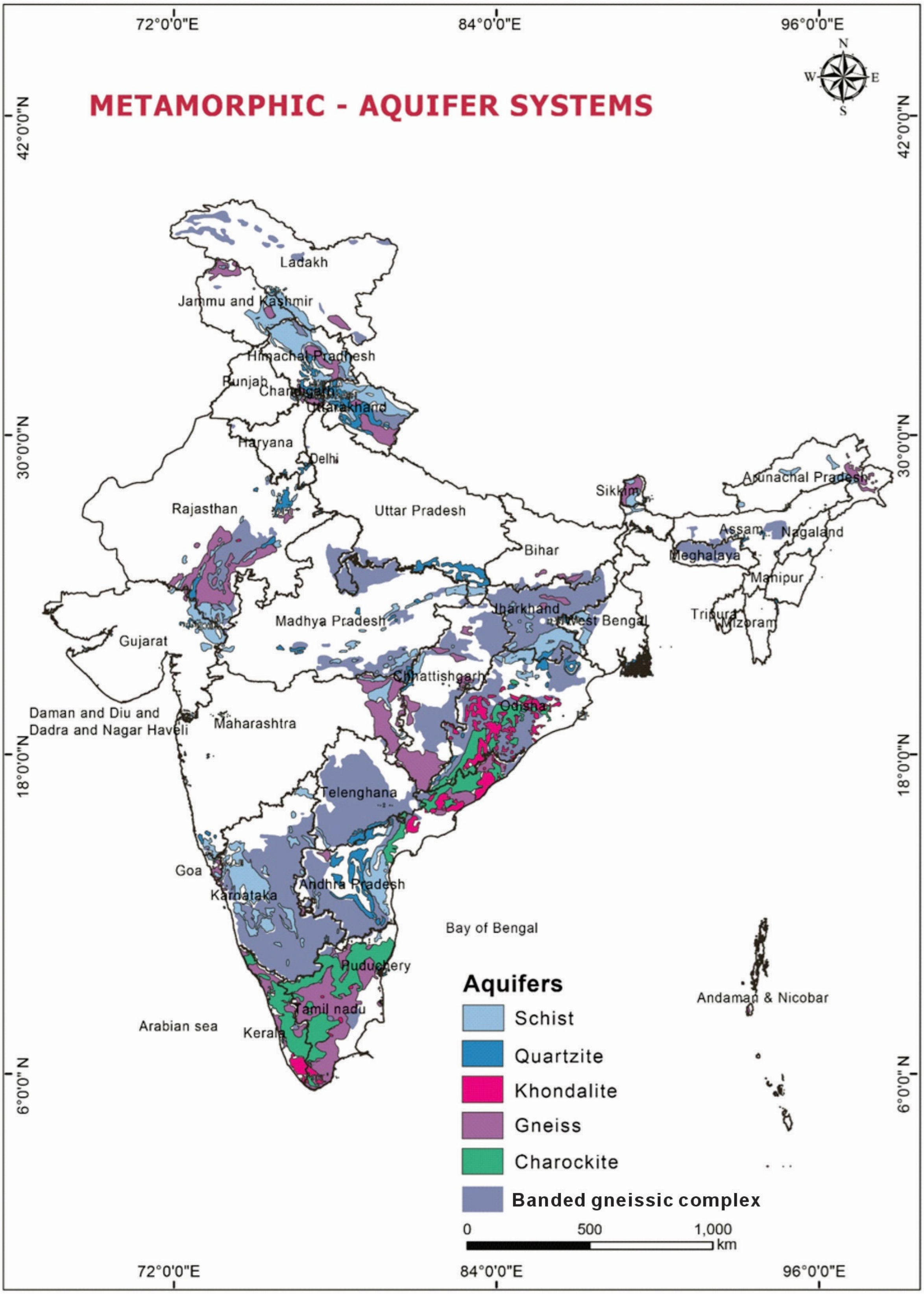


Fig. 3. Metamorphic aquifers of India, which are divided into six units (modified after CGWB, 2012, 2023).

Chhattisgarh (37756 km^2), Orissa (54951 km^2), Jharkhand (46174 km^2), Rajasthan (21506 km^2), Uttar Pradesh (9283 km^2).

The lowest thickness of banded gneissic aquifer weathered zone was observed from Andhra Pradesh (3–15 m), followed Meghalaya (5–15 m), and Orissa (12–15 m) and the maximum thickness in Jharkhand (up to 100 m), followed by Karnataka, Chhattisgarh, and Goa (up to 60 m). The fractures in banded gneissic aquifer extend to a maximum depth in Orissa (100–200 m), followed by Kerala (60–175 m), Rajasthan (60–170 m) and Tamil Nadu (60–170 m). The lowest depth was observed from Meghalaya (20–40 m), Andhra Pradesh (12–60 m), Meghalaya and followed by Andhra Pradesh (40–80 m). Transmissivity (m^2/day) in the banded gneissic aquifer is highest in Jharkhand (2–186), lowest in Orissa (5–15). The highest yield (m^3/day) observed from Jharkhand (24–3624) and Orissa (258–691) and the lowest yield from Kerala (2–10) and Meghalaya (5–10). All the banded gneissic aquifers are single aquifer Unconfined Semi-confined to Confined system.

2.2.2 Gneissic aquifer system

According to CGWB reports, India's gneissic aquifer system covers 0.51% of the country's land area, or 158753.26 km^2. The gneissic aquifer system is classified in to three: undifferentiated metamorphics, gneiss and migmatite. Undifferentiated metamorphics aquifer covers (59260 km^2), gneiss aquifer cover (43266 km^2), and migmatite gneiss aquifer covers (56228 km^2). The southern Indian states are mainly characterized by gneissic aquifer (Fig. 3) such as Tamil Nadu, and Kerala. Only four states are holding gneissic aquifer in India and Tamil Nadu is the largest migmatite gneiss aquifer in the country covering 51675 km^2, followed by Andhra Pradesh (3151 km^2), Rajasthan (1174 km^2), and Orissa (109 km^2). Kerala has 11980 km^2 of gneissic aquifer followed by Andhra Pradesh (7708 km^2), Maharashtra (7095 km^2) and Himachal Pradesh (4041 km^2). Undifferentiated metamorphics mainly occurs in Chhattisgarh (19679 km^2), followed by Rajasthan (17168 km^2), and Maharashtra (9481 km^2), and Uttarakhand (5735 km^2).

The lowest thickness of gneissic aquifer weathered zone is observed from Uttarakhand, and Himachal Pradesh (3–15 m) respectively and maximum from Jharkhand (up to 100 m), followed by Madhya Pradesh, Bihar, Tamil Nadu, and Maharashtra (up to 25 m). The fractures in gneissic aquifer encountered maximum depth from Rajasthan (200 m), followed by Madhya Pradesh (175 m), Uttarakhand (170 m) and Tamil Nadu (160 m). The lowest fractures zone was observed from Himachal Pradesh (20–40 m), Arunachal Pradesh (20–60 m), Andhra Pradesh and Rajasthan (20–80 m) respectively. Transmissivity (m^2/day) in the gneissic aquifer is highest in Kerala (14–80), and Uttarakhand (20–80) and the lowest in Himachal Pradesh (5–25), and Maharashtra (6–27). The highest yield (m^3/day) observed from Tamil Nadu (80–2500) and Rajasthan (14–864) and the lowest yield from Himachal Pradesh (50–70) and Maharashtra (10–80). All the banded gneissic aquifers are single aquifer systems with unconfined, semi-confined to confined aquifer type.

2.2.3 Schist aquifer system

According to CGWB reports, India's schist aquifer system covers 4.44% of the country's land area, or 140934 km^2 (CGWB, 2023) (Fig. 3). The schist aquifer system in this country is divided into three categories: schist, phyllite and slate. The total area of schist in India is 93026 km^2, phyllite is 31589 km^2 and slate is 16321. Karnataka covers the largest schist aquifer in India (28458 km^2) among India's 28 states, followed by Andhra Pradesh (13386 km^2) and Jammu and Kashmir hold (9365 km^2). Jharkhand covers (7703 km^2) of phyllite aquifer followed by Madhya Pradesh (4147 km^2), and Uttarakhand (3954 km^2) etc. only six states were observed slate aquifers and Himachal Pradesh covers majority of slate aquifers in India (12045 km^2) followed by Jammu and Kashmir (2288 km^2) and Uttarakhand (1191 km^2).

The hydrogeology of the schist aquifer consists of mainly single aquifer system, with confined, unconfined to semi-confined aquifer type. The lowest weathered thickness of schist km aquifer was observed from Bihar (4 m), and the maximum from Rajasthan (up to 80 m). The fractures in schist aquifer encountered maximum depth from Orissa (up to 180 m), and lowest from Himachal Pradesh (10 m). Transmissivity (m^2/day) in the schist aquifer is highest in Bihar (95), and the lowest in Jammu and Kashmir, Orissa, Himachal Pradesh, Gujarat, and Andhra Pradesh (nearly 2). The highest yield (m^3/day) observed from Karnataka (562) and the lowest yield from Himachal Pradesh (2.73–43.2).

2.2.4 Quartzite aquifer system

According to CGWB reports, India's quartzite aquifer system covers 1.48% of the country's land area, or 46904 km^2 (CGWB, 2023) (Fig. 3). Andhra Pradesh (11305 km^2) covers the largest schist aquifer in India among India's 28 states, followed by Uttarakhand (7033 km^2) Rajasthan (6456 km^2) and Uttar Pradesh (5378 km^2). etc.

The hydrogeology of the quartzite aquifer consists of mainly single aquifer system, with unconfined to semi-confined aquifer type. The lowest weathered thickness of quartzite aquifer was observed from Gujarat (5 m), and the maximum from Rajasthan (up to 30 m). The fractures in quartzite aquifer encountered maximum depth from Bihar and Rajasthan (up to 150 m), and lowest from Haryana (14 m). Transmissivity (m^2/day) in the quartzite aquifer is highest in Orissa (211), and the lowest in Haryana, Maharashtra, and Jharkhand (nearly 3). The highest yield (m^3/day) observed from Rajasthan and Gujarat (400) and the lowest yield from Haryana (2.76).

2.2.5 Charnockite aquifer system

India's charnockite aquifer system covers 2% of the country's land area, or 76360 km^2 (CGWB, 2023). Only seven states in India have charnockite aquifer in the country (Fig. 3) and the Tamil Nadu (33580 km^2) covering the largest charnockite aquifer in India, followed by Kerala (16071 km^2), and Andhra Pradesh (11302 km^2).

The hydrogeology of the charnockite aquifer consists of mainly single aquifer system, with unconfined to semi-confined aquifer type. The lowest weathered thickness of charnockite aquifer was observed from Kerala and Tamil Nadu (5 m), and the maximum from Rajasthan (up to 45 m). The fractures in charnockite aquifer encountered maximum depth from Chhattisgarh (up to 450 m), and lowest from Tamil Nadu and Andhra Pradesh (15 m). Transmissivity (m^2/day) in the charnockite aquifer is highest in Tamil Nadu (476), and the lowest in Andhra Pradesh and Rajasthan (nearly 5). The highest yield (m^3/day) observed from Kerala (3024) and Tamil Nadu (2500) the yield from Chhattisgarh and Rajasthan (2.5–10).

2.2.6 Khondalite aquifer system

India's khondalite (granulite facies metapelites) aquifer system covers 1% of the country's land area, or 32914 km^2 (CGWB, 2023) (Fig. 3). Only six states in India have khondalite aquifer in the country with Orissa (14351 km^2) covering the largest khondalite aquifers, followed by Andhra Pradesh (12091 km^2), and Kerala (4223 km^2).

The hydrogeology of the khondalite aquifer consists of mainly single units, with unconfined to semi-confined aquifer type. The weathered thickness of khondalite aquifer ranges from 5 to 20 m. The fractures in khondalite aquifer encountered at maximum depth (291 m) from Chhattisgarh and minimum from Kerala (40 m). Transmissivity (m^2/day) in the khondalite aquifer is highest in Tamil Nadu (476), and the lowest in Andhra Pradesh and Rajasthan (nearly 10). The highest yield (m^3/day) wells are observed from Tamil Nadu (1500).

2.3 Igneous crystalline aquifers (Fig. 4)

The igneous crystalline aquifers are represented by 3 distinct rocks types namely Deccan basalt (trap), granite, and mafic/ultramafic rocks. The details are given below.

2.3.1 Deccan basalt (trap) aquifer system

The vast area of Deccan basalts in central India is the major igneous aquifer and composed of alternate layers of compact and vesicular beds of lava flows (Fig. 4). The ground water occurrence in basalts is controlled by nature and extent of weathering, presence of vesicles and lava tubes, thickness of flows, number of flows and the nature of inter-trappean layers. Basaltic aquifers have usually medium to low permeability. Groundwater occurrence is controlled by the contrasting water bearing properties of different flow units, thus, resulting in multiple aquifer system, at places. The water bearing zones are the weathered and fractured zones. The permeability of basaltic aquifers is typically medium to low. The contrasting water-bearing characteristics of various flow units regulate the occurrence of groundwater in the traps, leading to the creation of multiple aquifer systems in certain areas. The cracked and worn areas are the ones that hold water. In India, 14 states are reported to have basaltic aquifers (CGWB, 2023). The basaltic aquifer system is divided into two categories: mafic and ultramafic. Maharashtra has wide spread basaltic aquifer in the country (235903 km^2) followed by Madhya Pradesh (135433 km^2), Gujarat (74297 km^2), Rajasthan (9794 km^2), Andhra Pradesh (9066 km^2), Jammu & Kashmir (6173 km^2), Jharkhand (3085 km^2), Arunachal Pradesh (1397 km^2), Chhattisgarh (836 km^2), Uttar Pradesh (572 km^2), West Bengal (244 km^2), Goa (35 km^2), and Bihar (34 km^2).

The lowest thickness of weathered zone is observed from Andhra Pradesh (5–20 m) and maximum from Goa (60 m), followed by Karnataka (10–45 m). The fractures in basalts encountered maximum depth from Gujarat (100–280 m), followed by Maharashtra (20–200 m) and Madhya Pradesh (60–175 m). The lowest depth was observed from West Bengal (35–90 m) and followed by Andhra Pradesh (40–80 m). Transmissivity (m^2/day) in the alluvium aquifer is highest in Andhra Pradesh (6–740), lowest in Chhattisgarh (5–50), followed by Jharkhand (26–176), but high yield (m^3/day) observed from Chhattisgarh (360–480) and Madhya Pradesh (70–350) and the lowest yield from Gujarat (1–30) and Maharashtra (45–90). In general, Madhya Pradesh, Maharashtra and Gujarat states have wide spread basalt aquifer system. All the basalt aquifers represent single and multiple system with unconfined to semi-confined type except in Maharashtra as it includes unconfined type also. The weathered basalts and vesicular basalts have higher transmissivities than fractured-jointed basalt and, therefore, form better aquifers.

2.3.2 Granitic aquifer system

India's granitic aquifer system covers 3.18% of the country's land area, or 100992 km^2 (CGWB, 2023) (Fig. 4). The granitic aquifer system in this country is divided into two categories: felsic volcanic rocks and felsic plutonic rocks. The total area of felsic volcanic rocks in India is 133 km^2 and felsic plutonic rocks is 100858 km^2. Gujarat covers the largest felsic volcanic rocks (115 km^2) among India's 28 states, followed by Rajasthan (18 km^2). Only few

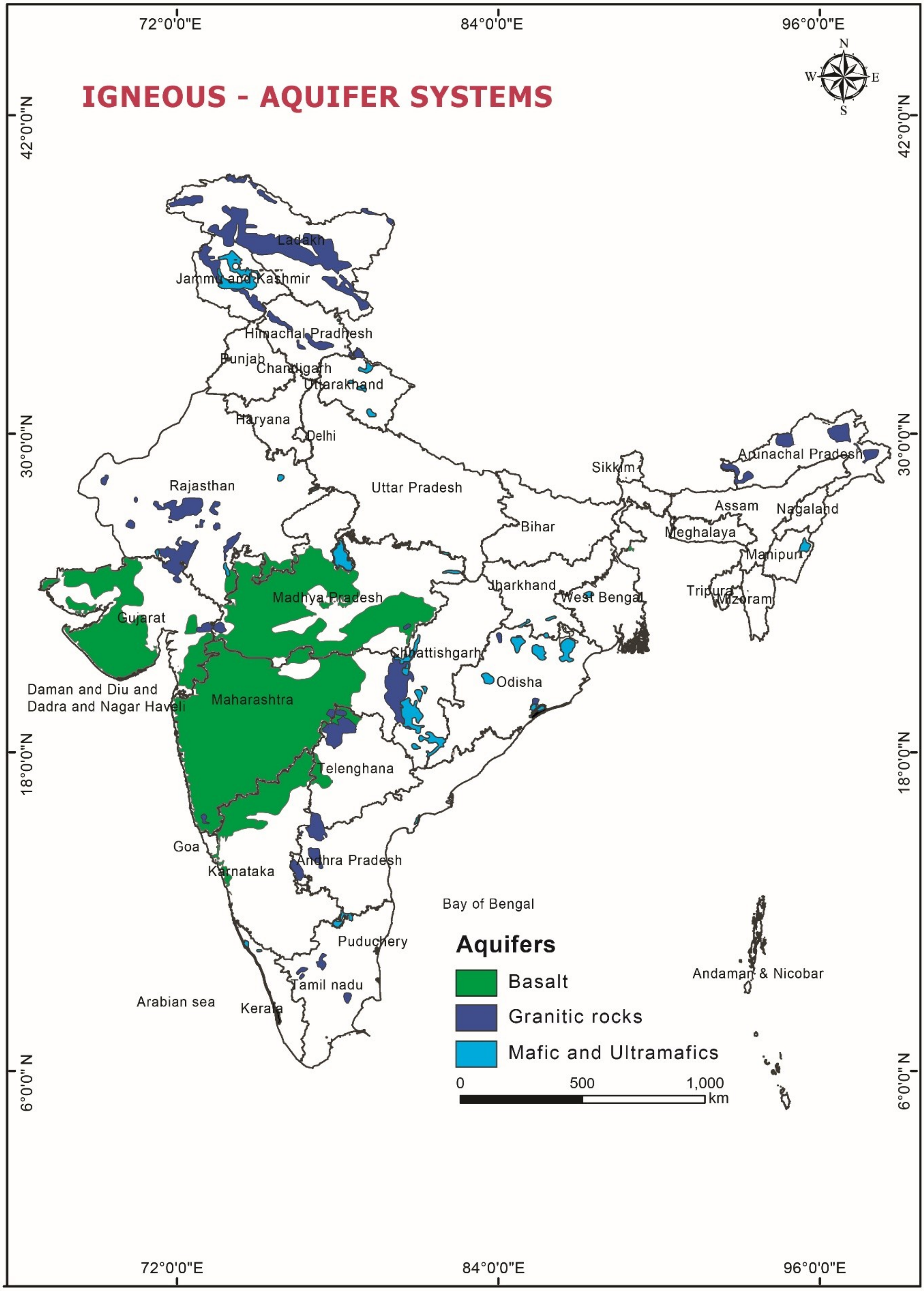


Fig. 4. Igneous aquifers of India, which are divided into three units (modified after CGWB, 2012, 2023).

states in India were observed felsic plutonic rocks. Jammu and Kashmir hold (39111 km^2) of intrusive acidic rocks followed by Andhra Pradesh (13597 km^2), Rajasthan (13190 km^2), Arunachal Pradesh (8672 km^2), and Maharashtra (7618 km^2).

The hydrogeology of the granitic aquifer consists of mainly single aquifer system, with confined, unconfined to semi-confined aquifer type. The lowest weathered thickness of granitic aquifer was observed from Himachal Pradesh and Uttarakhand (5–18 m), and the maximum from Jharkhand and Chhattisgarh (up to 40 m). The fractures in granitic aquifer encountered maximum depth from Tamil Nadu (200 m), and lowest from Andhra Pradesh (15 m). Transmissivity (m^2/day) in the granitic aquifer is highest in Tamil Nadu (500), and the lowest in Andhra Pradesh (2.3–12.6). The highest yield (m^3/day) observed from Tamil Nadu (288–1440) and the lowest yield from Gujarat (1–100).

2.3.3 Mafic and ultramafic aquifers

India's mafic/ultramafic aquifer system covers 0.63% of the country's land area, or 19896 km^2 and CGWB classified this aquifer as intrusives (CGWB, 2023) (Fig. 4). They are classified in to mafic, dolerite/anorthosite, metamorphosed mafic intrusive /granophyre and ultramafic. Mafic, dolerite/anorthosite covers (11167 km^2) and ultramafic covers (8729 km^2). Chhattisgarh (4352 km^2) hold largest dolerite/anorthosite and anorthosite aquifers in India followed by Orissa (2922 km^2) and Maharashtra (649 km^2). Jammu and Kashmir (4926 km^2) hold largest ultramafic, metamorphosed mafic intrusive/granophyre aquifers in India followed by Orissa (1948 km^2) and Nagaland (632 km^2).

The hydrogeology of these aquifer consists of mainly single aquifer system, with confined, unconfined to semi confined aquifer type. The weathered thickness of intrusive aquifer was observed from (6–13 m) and the groundwater fracture zone in intrusive aquifer encountered in different depths within the 150 m. Transmissivity (m^2/day) in the intrusive aquifer is not well studied and its ranges from 0.71–81. The highest yield (m^3/day) observed from 0.28–258.

3 Aquifer parameters

3.1 Vadose zone

The vadose zone plays a vital role in groundwater recharge in the different aquifer systems of India. This zone serves as the main pathway for rainwater and surface water to percolate down to the aquifers; however, its nature varies from place to place and from aquifer to aquifer. Its characteristics such as thickness, soil texture, porosity, and permeability are governed by the parent rocks and the degree of weathering. In regions like the Indo-Gangetic plains, sandy vadose zones enable rapid infiltration, while in peninsular crystalline terrains, clayey and weathered layers restrict recharge. The removal of topsoil from the vadose zone of an area for developmental activities severely affects groundwater recharge and its aquifer properties in many crystalline aquifers. Acting as a natural filter, the vadose zone improves water quality by trapping sediments and reducing contaminants, although excessive use of fertilizers, pesticides, and industrial effluents can still leach through and degrade groundwater. Since most recharge in India depends on the monsoon, the vadose zone also functions as a temporary reservoir that moderates seasonal fluctuations. Its significance is further evident in artificial recharge practices such as check dams and percolation ponds, where the effectiveness largely depends on vadose zone properties. Studies by Arora and Ahmed (2011) demonstrate that time-lapse electrical resistivity tomography (TLERT) is an effective tool for identifying preferential recharge pathways through fractures in the vadose zone of crystalline aquifers, providing insights beyond conventional point-based measurements. Thus, the vadose zone is a critical link between surface water and groundwater, directly influencing the sustainability and quality of India's aquifer systems.

3.2 Major aquifer parameters

Aquifers in India vary widely in their parameters depending on geological formations, hydrological conditions, and anthropogenic influences. The various parameters are listed below.

(a) Geological Formation: India has diverse geological formations ranging from alluvial plains to crystalline (hard rock) regions. Aquifers can be found in sedimentary formations like alluvium, sandstone, and limestone, as well as fractured rock formations like granite and basalt.

(b) Porosity: Porosity refers to the percentage of void spaces in the rock or sediment that can hold water. Alluvial aquifers generally have higher porosity compared to fractured rock aquifers.

(c) Permeability: Permeability measures the ability of the rock or sediment to transmit water. Aquifers with higher permeability allow water to flow more easily. For example, alluvial aquifers typically have higher permeability than crystalline rock aquifers.

(d) Recharge rate: Recharge rate is the rate at which water enters the aquifer, typically through precipitation or surface water infiltration. It varies depending on factors like rainfall patterns, land use, and surface water availability.

(e) Depth: Aquifers can occur at different depths below the ground surface, ranging from shallow to deep

Aquifer	Yield (m^3/day)	Specific yield (%)	Transmissivity (m^2/day)
Alluvium	10–6500	6–18	2–1600
Laterite	5–6000	2–9	2–1500
Basalt	1–480	1–3	5–740
Sandstone	5–3700	1.5–15	3–6000
Shale	8–2900	1–3	10–740
Limestone	4–2100	2–3	1.2–450
Granite	10–1440	2–3	0.32–500
Schist	3–550	1.2–5.2	2–95
Quartzite	2–400	1–2.5	2.7–211
Charnockite	1–3000	2–5	5–476
Khondalite	20–1500	2–3	10–476
Banded Gneiss	2–3600	1.5–3	2–186
Gneiss	10–2500	1.5–5	5–80
Mafic/ultramafic	Low Yield	1.5–2	0.71–81

Table 1. The salient properties of the major aquifer systems in India.

aquifers. Shallow aquifers are often more susceptible to contamination, while deeper aquifers may have higher quality water but require more energy for extraction.

(f) Storage Capacity: Storage capacity refers to the volume of water that can be stored in the aquifer. It depends on factors like porosity, thickness of the aquifer, and degree of saturation. These parameters are critical for understanding the dynamics of groundwater flow, sustainability of extraction, and vulnerability to contamination in different regions of India.

Table 1 shows the transmissivity and specific yield values of the aquifers (source: CGWB, 2023). Transmissivity is a measure of the ability of an aquifer to transmit water horizontally under a hydraulic gradient. In India, the transmissivity of aquifers varies significantly across different regions due to variations in geological formations and hydrological conditions. For instance: Alluvial aquifers, predominant in regions like the Indo-Gangetic plains, typically exhibit high transmissivity due to their sandy and gravelly nature, allowing for significant horizontal movement of water. In contrast, aquifers in crystalline regions, such as parts of peninsular India, have lower transmissivity due to the presence of fractured rock formations, which offer less continuous pathways for water flow compared to alluvial deposits. Sandstone, laterite and alluvial aquifers of India show highest transmissivity values.

Specific yield, also known as drainable porosity, is the ratio of the volume of water that an aquifer will yield by gravity to the volume of the aquifer material. It represents the amount of water released from storage per unit decline in hydraulic head in an unconfined aquifer. Specific yield values in India can vary depending on factors such as lithology, porosity, and degree of saturation. Alluvial aquifers generally have higher specific yield values due to their higher porosity and greater capacity to store and release water. Fractured rock aquifers may have lower specific yield values compared to alluvial aquifers due to the presence of less permeable rock matrix interspersed with fractures.

4 Estimation of groundwater resources

4.1 Dynamic groundwater resource (shallow aquifer)

Groundwater resource assessment in India is carried out periodically through joint efforts of the State Ground Water Departments and the Central Ground Water Board (CGWB), under the supervision of the Central Level Expert Group (CLEG). These assessments, undertaken since 1980 and conducted annually and estimates dynamic groundwater resources, extractable resources, utilization, and the stage of extraction. Until 2017, the methodology followed the Ground Water Estimation Committee (GEC-97) guidelines, whereas subsequent assessments adopt the revised GEC-2015 methodology. Rainfall remains the principal source of recharge, contributing about 61% of the total, though its distribution varies widely across the country. Recharge potential is also strongly influenced by geological formations, with alluvial aquifers showing high storage and transmission properties compared to fissured crystalline terrains.

The 2024 assessment estimated the total annual groundwater recharge at 446.90 BCM and extractable resources at 406.19 BCM, with extraction reaching 245.64 BCM, giving a national average stage of extraction of 60.47% (CGWB, 2024). Out of 6746 assessment units, 11.13% were categorized as over-exploited, 3.05% as critical, 10.54% as semi-critical, 73.39% as safe, and 1.88% as saline. Delhi, Haryana, Punjab, Rajasthan, and Tamil Nadu show particularly high proportions of over-exploited and critical units. Spatially, groundwater stress is concentrated in northwestern India (due to excessive withdrawals despite abundant recharge), western arid regions (limited recharge), and southern peninsular states (low-yield crystalline aquifers). In contrast, improvements have been observed in some regions owing to favourable rainfall and government-supported conservation and augmentation initiatives. (The terms “safe,” “semi-critical,” “critical,” and “over-exploited” are official classifications used by the Central Ground Water Board (CGWB), Government of India, to indicate groundwater extraction status at the administrative block level. These terms are specific to India’s groundwater management framework and do not represent standard hydrogeological categories used internationally. (for details see https://www.cgwb.gov.in/en/ground-water-resource-assessment.))

The Central Ground Water Board (CGWB), along with state groundwater departments, currently carries out groundwater resource estimation on a block-wise administrative basis, since groundwater management decisions are linked to governance and policy frameworks at district and state levels. While this approach ensures ease of planning and regulation, it often overlooks the natural hydrogeological boundaries that control recharge, discharge, and groundwater flow. In contrast, watershed-based estimation provides a more scientific framework, aligning with natural hydrological units and enabling better understanding of groundwater dynamics, sustainable management, and conservation practices. Hence, efforts should be taken to gradually shift groundwater resource estimation from administrative units to a watershed-wise framework across the country.

4.2 Deeper aquifers

In recent decades, rapid population growth, urbanization, and technological advancement have led to intensified dependence on deeper aquifers, whereas until the late twentieth century groundwater extraction was largely confined to shallow aquifers that were generally considered safe and free from microbial and particulate contamination (Saha and Ray, 2018). However, reliable estimates of deeper aquifer reserves are still lacking, unlike the systematic assessments available for dynamic groundwater resources. Given the complexity and significance of deeper aquifers in India’s groundwater landscape, conducting comprehensive estimations and assessments of these resources is highly essential. Deeper aquifers often serve as critical reserves, especially in regions where shallower aquifers are depleted or overexploited. By focusing on deeper aquifers, we can gain a more holistic understanding of India’s groundwater potential and develop targeted management strategies to ensure sustainable utilization.

The in-depth hydrogeological studies to understand the characteristics, recharge mechanisms, and groundwater flow dynamics of deeper aquifers involve special groundwater exploration programmes with high-capacity rigs, assessing aquifer properties, and identifying potential recharge sources. Establishing a robust monitoring network to collect data on groundwater levels, quality, and extraction rates is crucial for estimating the reserves of deeper aquifers. The NAQUIM project, led by the Central Ground Water Board (CGWB) is a novel step which focuses on comprehensive aquifer mapping, both phreatic and deeper aquifers. It integrates data collection, hydrological modeling, and stakeholder engagement to create actionable plans for efficient and sustainable groundwater use. Utilizing advanced exploration techniques such as aquifer mapping, geophysical surveys, remote sensing, and groundwater modeling to delineate the extent and thickness of deeper aquifers. These techniques can provide valuable insights into the aquifer properties and facilitate more accurate estimations of groundwater reserves.

4.3 Aquifer de-saturation

Aquifer desaturation, driven by over-extraction of groundwater and exacerbated by climate change, poses a significant threat to global water security. Excessive pumping of groundwater for agricultural, industrial, and domestic needs has led to declining water tables in many regions, particularly in urban areas where recharge rates are naturally low. A simplified cartoon representation of this phenomenon is presented in Fig. 5a and b. These figures illustrate a comparison of the water table between the present and 10 years ago, alongside a visual depiction of aquifer desaturation. Despite clear evidence of aquifer depletion, the observed water table fluctuations remain relatively unchanged over the years. This apparent stability can be misleading, as it masks the underlying desaturation processes occurring within the aquifers. The deceptive nature of these water table readings may result in overestimations of groundwater resources, as they fail to account for the reduced storage capacity caused by long-term over-extraction and compaction of aquifer materials. This over-extraction accelerates aquifer depletion, reducing water availability and increasing vulnerability to droughts. Climate change further compounds this issue by altering precipitation patterns, increasing evapotranspiration, and reducing recharge rates, leading to a mismatch between groundwater extraction and natural replenishment. The combined effects result in aquifer desaturation, land subsidence, saltwater intrusion in coastal areas, and loss of groundwater-dependent ecosystems.

Coastal areas are particularly vulnerable to saltwater intrusion due to rising sea levels. Prolonged droughts

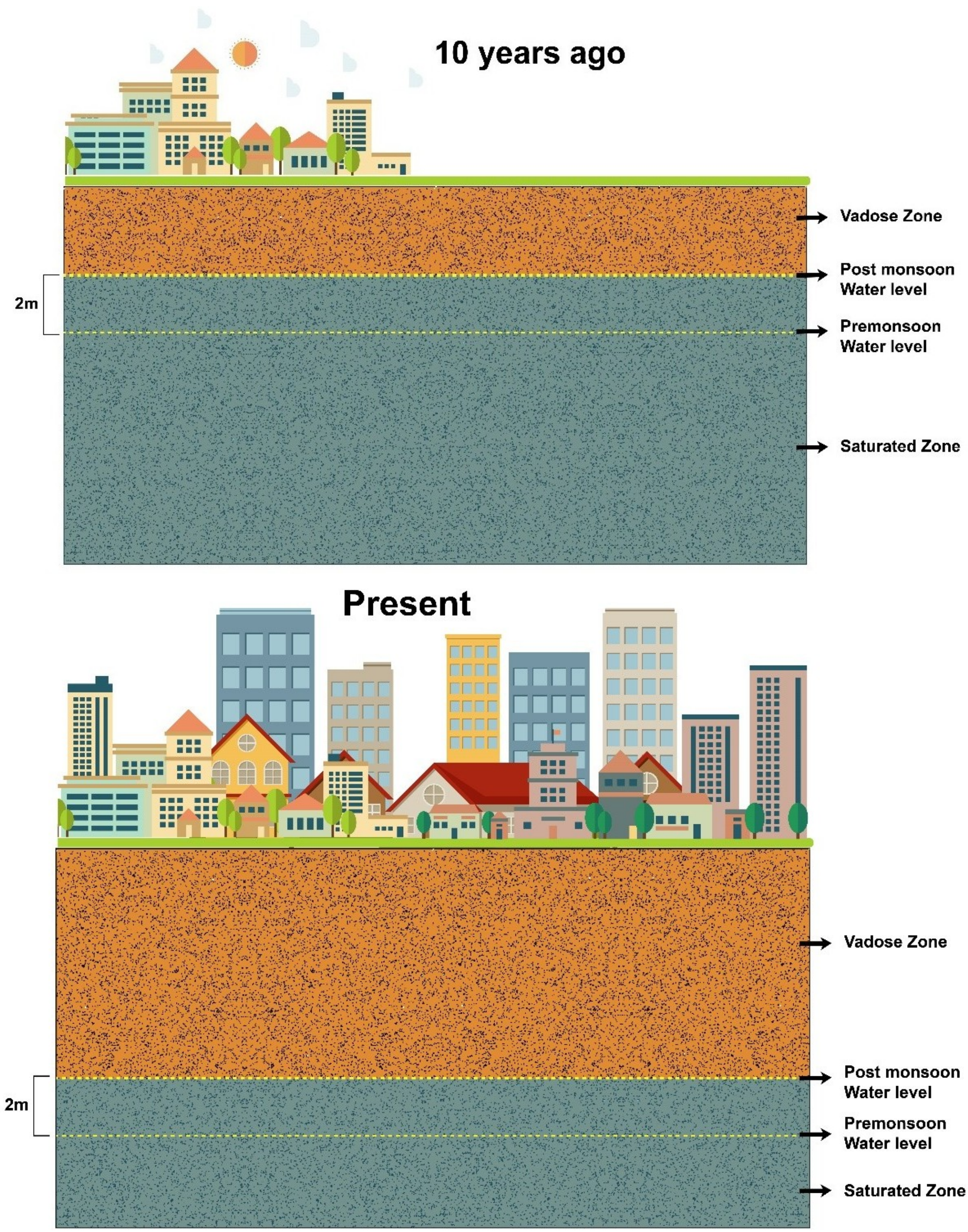


Fig. 5. Comparison of the water table levels and Visual depiction of aquifer desaturation and its impact on groundwater availability. (a) 10 years ago (b) Current water table, highlighting changes over time.

exacerbate water stress, pushing more reliance on over-exploited groundwater sources and compromising water availability. Effective management strategies, such as enhanced monitoring, sustainable practices, and policy interventions, are crucial to mitigating these impacts and ensuring the long-term viability of groundwater resources. Many studies emphasize the importance of developing policies that address both climate change and groundwater management, as these must be tailored to local contexts to support sustainable growth. Groundwater is essential for achieving the United Nations' sustainable development goals. (Davamani et al., 2024).

5 Discussion

Over-exploitation of groundwater has become a global concern, leading to declining water table, reduced storage capacity, land subsidence, and long-term threats to water security and ecosystem sustainability (Li and Elumalai, 2025). The diverse aquifer systems across India play a crucial role in the country's water resource management and agricultural practices. Each aquifer system has its unique characteristics and distribution, impacting the availability and quality of groundwater in different regions.

Firstly, the alluvial aquifer system dominates the north-western and north-eastern states, along with some parts of southern coastal regions. This system, covering a significant portion of India's land area, provides vital groundwater resources for irrigation, especially in the fertile plains of the Indo-Gangetic belt. The extensive cultivation of crops like rice, wheat, maize, sugarcane, and cotton heavily relies on groundwater from these aquifers. However, over-exploitation in certain areas, as indicated by the 'over-exploited' categories, poses a threat to sustainable water management. The over-exploited blocks overlaid on the aquifer units are presented in Fig. 6, providing a clear spatial representation of groundwater stress. Severe over-exploitation of groundwater is noticed in the sedimentary aquifers of the Indo-Gangetic alluvial system. Regions such as Haryana, Punjab, Rajasthan, and Delhi face significant challenges due to excessive extraction (Fig. 6). This has led to declining water tables and increasing scarcity, impacting agriculture, industry, and urban water supply. In southern India, specifically in Tamil Nadu and Karnataka, the issue is also pronounced in metamorphic crystalline aquifers, notably in urban centres like Bangalore and Chennai (Fig. 6). The unsustainable use of groundwater in these areas poses serious threats to water security and necessitates urgent conservation and management efforts. Decades of intensive agricultural practices, coupled with rapid urbanization and industrialization, have led to the unsustainable extraction of groundwater from these aquifers. The demand for water has far exceeded the natural recharge rates, resulting in a significant decline in groundwater levels.

This over-extraction poses several serious consequences. Firstly, it threatens the long-term sustainability of agricultural production, which heavily relies on groundwater for irrigation. As water levels drop, farmers are forced to drill deeper wells, incur higher pumping costs, and face reduced yields. This can ultimately lead to land degradation, loss of livelihoods, and food insecurity.

Furthermore, the depletion of groundwater in the Indo-Gangetic alluvium has broader ecological implications. It affects the flow of rivers and streams, disrupts ecosystems, and exacerbates water scarcity issues in both rural and urban areas. Additionally, the intrusion of saline water into freshwater aquifers due to excessive pumping further compounds the problem, rendering the water unfit for agricultural use.

Addressing the issue of groundwater over-extraction in the Indo-Gangetic alluvium requires a multi-faceted approach. It involves implementing sustainable water management practices such as promoting water-efficient irrigation techniques, incentivizing crop diversification, and regulating groundwater extraction through policies and regulations. Moreover, community involvement, awareness campaigns, and the adoption of groundwater recharge initiatives are essential to replenish depleted aquifers and restore their natural balance.

In conclusion, tackling groundwater over-extraction in the Indo-Gangetic alluvium is crucial for ensuring the long-term viability of agriculture, safeguarding ecosystems, and preserving water security for millions of people. It requires concerted efforts from policymakers, stakeholders, and communities to implement sustainable solutions that balance the needs of agriculture with the conservation of precious water resources.

Severe problems in the crystalline aquifers are noticed from Maharashtra, Madhya Pradesh, and Gujarat and the southern part of peninsular India including parts of Karnataka, Tamil Nadu Telangana, and Andhra Pradesh.

In the case of basalt aquifer system, predominantly found in states like Maharashtra, Madhya Pradesh, and Gujarat contributing to agricultural activities in these regions. With its mafic and ultra-mafic categories, this system supports groundwater recharge but the groundwater is not enough farming practices.

The banded gneissic complex (BGC) aquifer system, prevalent in states like Karnataka, Andhra Pradesh, and Tamil Nadu, underscores the importance of geological diversity in groundwater distribution. These aquifers, covering significant land areas, cater to agricultural needs and highlight the need for careful management to ensure long-term sustainability. Regions like Bangalore faces decline of groundwater levels due to over exploitation from these aquifers.

Similarly, the gneissic aquifer system, granitic aquifer system, and charnockite aquifer system, though covering relatively smaller land areas compared to alluvium and basalt systems, are essential contributors to groundwater resources in their respective regions. Their presence in southern states like Tamil Nadu, Kerala, and Karnataka highlights the geological variability across the country.

Moreover, aquifer systems like schist, quartzite, lateritic, sandstone, shale, and limestone each have their

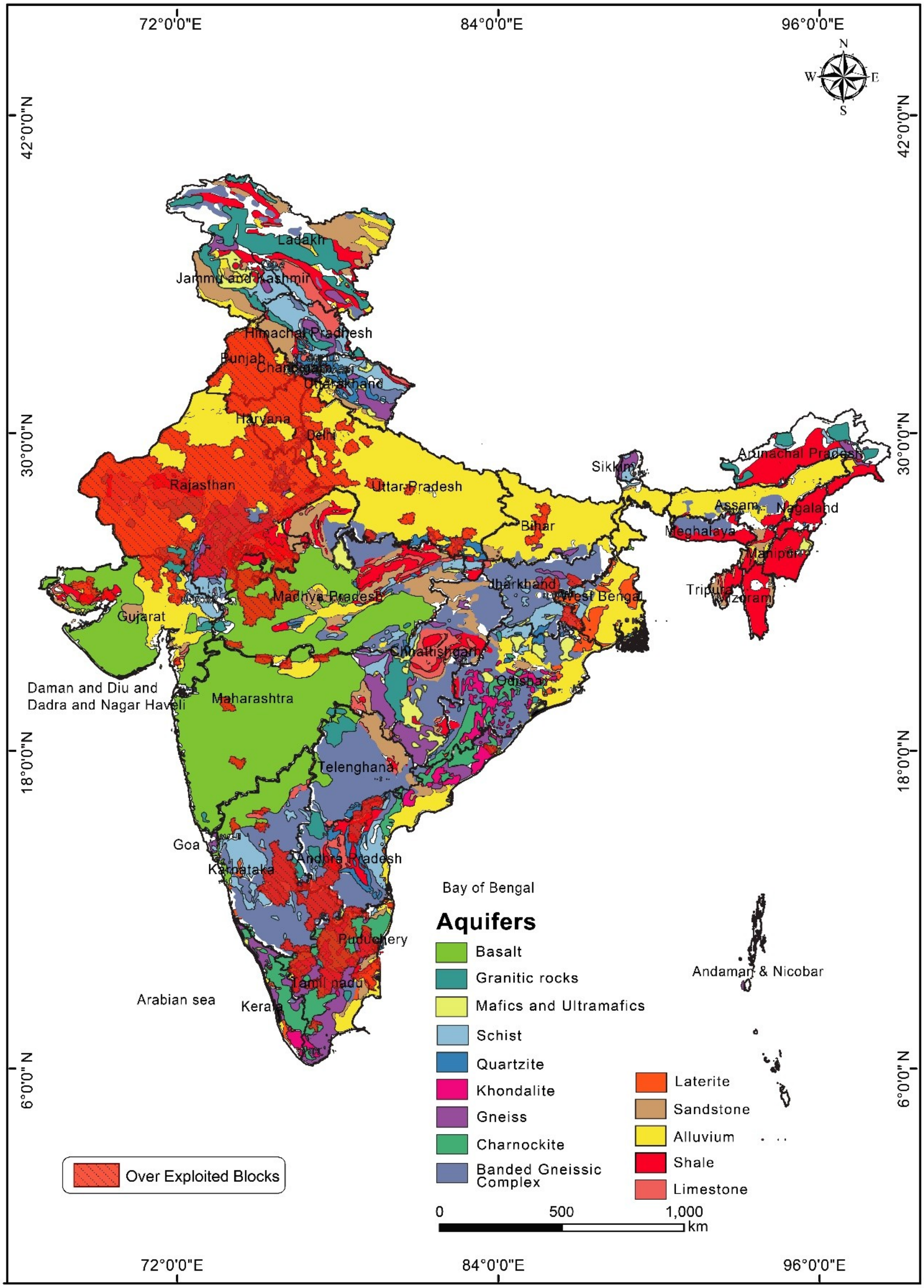


Fig. 6. Spatial representation of groundwater stress, showing over-exploited blocks overlaid on aquifer units. Note that the sedimentary and metamorphic aquifers were exploited more than the igneous aquifers (modified after CGWB, 2012, 2023, 2024).

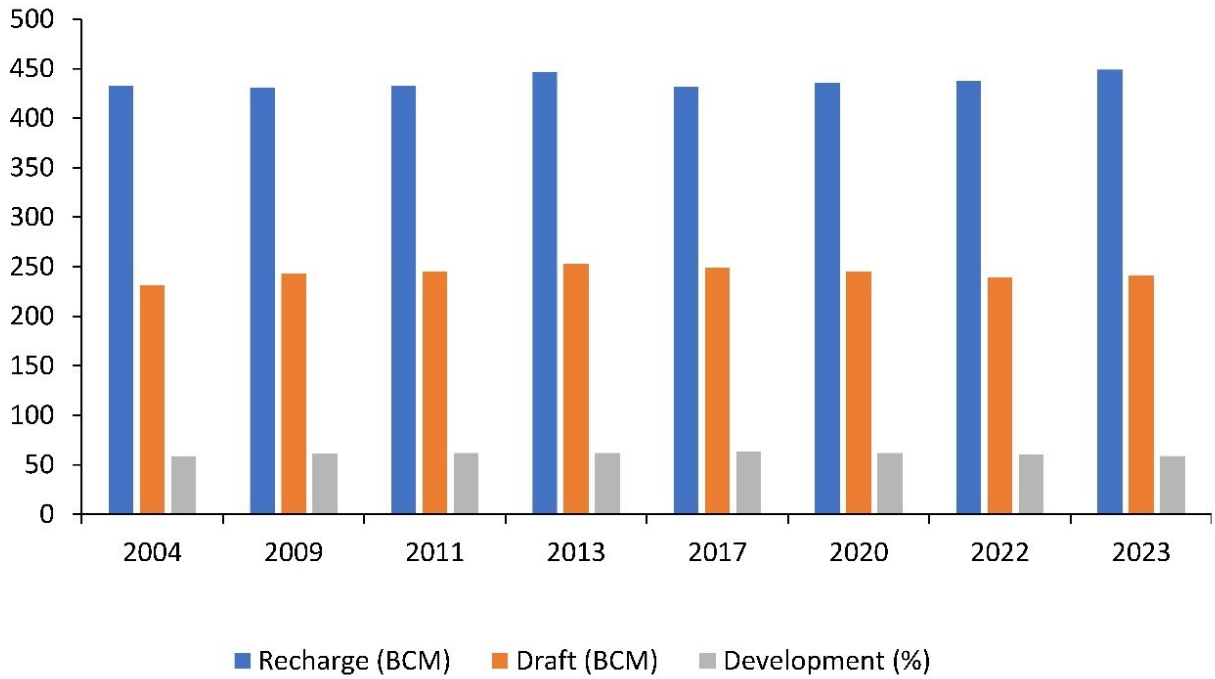


Fig. 7. Histogram of the recharge, draft, and stage of development of groundwater in India from 2004 to 2023. (Source: CGWB, 2023, 2024).

roles in groundwater availability and usage. Whether it's the sandstone aquifer system supporting water needs in states like Jammu and Kashmir or the shale aquifer system contributing to water resources in various regions, the diverse geological formations significantly influence India's water landscape.

Fig. 7 shows a histogram of the recharge, draft, and stage of development on India from 2004 to 2023, where there are no significant variations in the overall groundwater recharge, extraction from the aquifers (draft) and the stage of groundwater development in the country. However, there is a considerable imbalance in the availability of groundwater resources across the length and breadth of the India. Severe over exploitation is observed from mainly from Haryana (135%), Punjab (163%), Rajasthan (148%), and Delhi (99%), i.e., from Indo-Gangetic alluvial aquifers. The issue of groundwater over-extraction in the Indo-Gangetic alluvium is a pressing concern that demands immediate attention. The alluvial aquifers in the Indo-Gangetic plains serve as a lifeline for agriculture, providing vital water resources for irrigation in one of the world's most densely populated regions.

However, amidst the richness of aquifer systems, challenges such as over-extraction, contamination, and depletion loom large. Sustainable management practices, including managed groundwater recharge initiatives, monitoring extraction rates, and promoting water-efficient farming techniques, are imperative to ensure the long-term viability of India's groundwater resources. The varied aquifer systems across India emphasize the country's hydrogeological complexity and the importance of holistic water management strategies to sustainably meet the water needs of its growing population, agricultural and industrial sector.

6 Sustainability and innovative solutions

Groundwater sustainability in India is challenged not only by over-extraction and declining water levels but also by institutional and policy failures. Fragmented water governance, weak regulation of borewell drilling, and perverse incentives such as free electricity for irrigation have accelerated unsustainable withdrawals, particularly in agriculturally intensive regions. Although initiatives like NAQUIM and assessments by the CGWB have improved aquifer knowledge, they often fall short of addressing these systemic issues. Climate change further compounds the crisis, with IPCC AR6 projecting that northwest India will face declining effective recharge by the mid-21st century due to shorter, more intense monsoons and reduced winter precipitation, while eastern and coastal regions may witness more flash recharge events with low infiltration efficiency (Shaw et al., 2022). Rising mean annual temperatures are projected to increase potential evapotranspiration (PET) by 5–20% across much of India by 2050 (Yahaya et al., 2024). This will significantly intensify irrigation water demand, further straining already overexploited groundwater resources. Achieving groundwater sustainability in India, therefore, requires integrating scientific aquifer assessments with stronger regulatory frameworks, demand-side management, and climate-resilient water governance.

Therefore, we propose the integration of following innovative solutions for the estimation and management of groundwater resources to ensure sustainable water use and mitigating the challenges posed by overexploitation and contamination.

(a) Remote Sensing and GIS Technologies: Utilize high resolution data from Interferometric Synthetic Aperture Radar, Gravity Recovery and Climate Experiment, Light Detection and Ranging, Airborne Electromagnetic Systems, and satellite altimetry.

(b) Advanced Hydrogeological Modelling: Develop advanced hydrogeological models using numerical simulation techniques to simulate groundwater flow, predict aquifer behaviour, and evaluate the impacts of various management strategies. Incorporate factors such as climate change, land use changes, and groundwater-surface water interactions into these models for improved accuracy.

(c) Aquifer Recharge Enhancement: Implement innovative techniques for enhancing aquifer recharge, such as artificial recharge through the construction of recharge structures like percolation ponds, recharge wells, and subsurface dams. Explore the potential of managed aquifer recharge (MAR) systems, including infiltration basins and recharge trenches, to replenish groundwater supplies during periods of low rainfall.

(d) Smart Monitoring Systems: Deploy smart monitoring systems equipped with sensors and IoT (Internet of Things) technology to continuously monitor groundwater levels, quality parameters, and extraction rates in real-time. These systems can provide valuable data for adaptive management decisions and early warning of potential groundwater depletion or contamination issues.

(e) Integrated Water Resource Management: Promote integrated water resource management approaches that consider the interconnectedness of surface water and groundwater systems. Develop collaborative frameworks involving stakeholders from various sectors to coordinate water allocation, promote water conservation practices, and minimize conflicts over water resources. Innovative Conservation and Demand Management: Implement innovative conservation measures and demand management strategies to reduce water usage and minimize groundwater withdrawals. Encourage the adoption of water-efficient technologies, rainwater harvesting systems, and water reuse/recycling practices in agriculture, industry, and urban areas.

(f) Community Engagement and Capacity Building: Foster community participation and stakeholder engagement in groundwater management initiatives through awareness campaigns, training programs, and participatory decision-making processes. Empower local communities to take ownership of their groundwater resources and implement sustainable water management practices.

(g) Predictive Modelling: AI algorithms, such as machine learning and deep learning, can be trained on historical groundwater data to develop predictive models for groundwater levels, quality, and recharge rates. These models can forecast future trends, enabling proactive management and resource allocation. AI techniques can analyze geospatial data, hydrological parameters, and geological information to characterize aquifers more accurately. By identifying key aquifer properties and boundaries, AI helps improve understanding of groundwater flow dynamics and optimize resource management strategies.

(h) Optimization of Pumping Schedules: AI-based optimization algorithms can optimize pumping schedules for groundwater extraction to maximize water availability while minimizing energy costs and environmental impacts. These algorithms consider factors such as demand patterns, aquifer recharge rates, and pumping constraints to achieve sustainable groundwater management.

(i) Real-time Monitoring and Early Warning Systems: AI-powered sensor networks and data analytics enable real-time monitoring of groundwater levels, quality parameters, and extraction rates. By analyzing streaming data, AI algorithms can detect anomalies, identify trends, and issue early warnings of potential groundwater depletion or contamination events.

(j) Decision Support Systems: AI-driven decision support systems integrate diverse datasets, simulation models, and optimization algorithms to assist water managers in making informed decisions. These systems provide actionable insights and scenario analysis for evaluating the effectiveness of various management strategies and policy interventions.

(k) Groundwater Quality Assessment: AI algorithms can analyze multi-dimensional datasets, including hydrochemical data, satellite imagery, and land use information, to assess groundwater quality and detect contamination sources. These tools help identify vulnerable areas, prioritize monitoring efforts, and implement targeted remediation measures.

(l) Smart Irrigation Management: AI-powered irrigation systems use real-time weather data, soil moisture sensors, and crop models to optimize irrigation scheduling and water use efficiency. By dynamically adjusting irrigation volumes and timing based on plant water needs and environmental conditions, these systems reduce water wastage and minimize groundwater depletion.

(m) Data Fusion and Integration: AI techniques facilitate the fusion and integration of heterogeneous data sources, including satellite imagery, geophysical surveys, and groundwater monitoring networks. By aggregating and analyzing diverse datasets, AI tools enable holistic assessments of groundwater resources and support integrated water resource management initiatives.

7 Conclusion

The complex geological diversity of India greatly influences groundwater recharge and availability. The sedimentary porous formations like alluvial deposits in the Indo-Ganga-Brahmaputra basin typically have high specific yields and serve as significant groundwater reservoirs. In contrast, groundwater occurrence in igneous and metamorphic aquifers, which cover a large portion of the country, is mostly limited to weathered, jointed, and fractured sections of rocks. These aquifers cannot be considered perennial and sustainable groundwater sources. The present total annual groundwater recharge in India is estimated to be 446.90 BCM, with an extractable groundwater resource assessed at 406.19 BCM. However, the annual groundwater extraction is 245.64 BCM, indicating a substantial utilization of available resources. The average stage of groundwater extraction for the country is approximately 60.47%. A significant concern is the over-exploitation of groundwater resources in certain regions. Among all aquifers, about 11% of assessment units are categorized as 'Over-exploited,' where groundwater extraction exceeds recharge rates. Additionally, 3% of assessment units are classified as 'Critical,' indicating a stage of groundwater extraction between 90–100%. Over time, there have been changes in groundwater assessments, with refinements in methodologies and changes in assessment units. While some areas have shown improvement due to recharge practices, challenges persist in regions facing over-exploitation, arid climates, and low groundwater availability due to hydrogeological characteristics. Adopting a watershed-based approach nationwide would ensure that groundwater management is guided by natural hydrogeological principles rather than administrative convenience. This review highlights the escalating crisis of groundwater overuse in India. Groundwater overuse occurs in all aquifers when the average extraction rate from aquifers surpasses the average recharge rate over time.

Therefore, groundwater resource assessment requires continuous monitoring and refinement to address evolving challenges and ensure sustainable management of this vital resource. This review highlights the need to estimate deeper groundwater resources of India to address the growing issue of over-exploitation of phreatic aquifers in certain pockets. India's diverse aquifer systems form the bedrock of the nation's water resources and agricultural productivity. From the expansive alluvium aquifers of the Indo-Gangetic plains to the basaltic formations of Maharashtra and the crystallines of southern India, each aquifer contributes uniquely to groundwater availability and sustenance. Therefore, CGWB may establish a comprehensive national groundwater information system that provides both daily and historical data to the public for informed decision-making and sustainable water management. Such initiatives are integral to achieving water security, promoting sustainable development, and mitigating the impacts of groundwater depletion and degradation. However, alongside their invaluable contributions, these aquifer systems face significant challenges such as over-exploitation, contamination, and depletion. Addressing these challenges requires a concerted effort towards sustainable water management practices, including managed aquifer recharge initiatives, efficient irrigation techniques, and stringent monitoring of extraction rates. By recognizing the importance of aquifer systems and implementing measures for their preservation and replenishment, state groundwater authorities should be strengthened and empowered to function effectively under the guidance of the Central Ground Water Authority of India. This not only secures the country's agricultural livelihoods but also safeguards the broader ecological balance and the well-being of its citizens for generations to come. This review suggests to develop strategies for advancing hydrogeology in the new era through enhanced research, monitoring, data sharing, citizen science, international cooperation, cross-sector collaboration among academia, industry, research institutes, and governments, and sustained governmental support to ensure the sustainable management and protection of groundwater resources globally.

Acknowledgements

The authors gratefully acknowledge the Chairman, members, and scientists of the Central Ground Water Board (CGWB) for bringing out valuable scientific reports on India's groundwater and making them accessible in the public domain.

We thank the handling Editor-in-Chief of the Journal and three anonymous referees for constructive comments during two rounds of review and revision that greatly improved this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Co-author M. Santosh is Executive Advisor of this Journal and was not involved in the editorial review or the decision to publish this article.

Credit Author Statement

E. Shaji: Conceptualization, Investigation, Supervision, Validation, Writing—original draft.

M. Santosh: Visualization, Validation; Writing—review & editing.

K.V. Sarath: Data curation, Formal analysis, Investigation, Writing—original draft.

P.K. Krishnaprasad: Data curation, Formal analysis; Validation.

G. Indu: Data curation, Formal analysis; Validation.

S.G. Dhanil Dev: Validation.

References

Arora, T., Ahmed, S., 2011. Characterization of recharge through complex vadose zone of a granitic aquifer by time-lapse electrical resistivity tomography. Journal of Applied Geophysics 73(1), 35–44. doi:10.1016/j.jappgeo.2010.11.003.

Central Ground Water Board (CGWB). Official Website: URL: http://cgwb.gov.in.

CGWB, 2012. Central Ground Water Board report on Aquifer system of India. URL: https://www.aims-cgwb.org/principal-aquifer-systems-india.php.

CGWB, 2022. Dynamic Groundwater Resources of India. URL: https://cgwb.gov.in/cgwbpnm/public/uploads/documents/16862159959508359934file.pdf.

CGWB, 2023. Dynamic Groundwater Resources of India. URL: https://cgwb.gov.in/cgwbpnm/public/uploads/documents/17056512151889452705file.pdf.

CGWB, 2024. Dynamic Groundwater Resources of India. URL: https://cgwb.gov.in/cgwbpnm/public/uploads/documents/17357182991031590738file.pdf.

Dangar, S., Asoka, A., Mishra, V., 2021. Causes and implications of groundwater depletion in India: a review. Journal of Hydrology 596, 126103. doi:10.1016/j.jhydrol.2021.126103.

Das, S., 2023. Groundwater sustainability, security and equity: India Today and Tomorrow. Journal of the Geological Society of India 99(1), 5–8. doi:10.1007/s12594-023-2260-x.

Davamani, V., John, J.E., Poornachandhra, C., Gopalakrishnan, B., Arulmani, S., Parameswari, E., Santhosh, A., Srinivasulu, A., Lal, A., Naidu, R., 2024. A critical review of climate change impacts on groundwater resources: a focus on the current status, future possibilities, and role of simulation models. Atmosphere 15(1), 122. doi:10.3390/atmos15010122.

Dey, S., Singh, S., Raju, N.J., Mall, R.K., 2024. Hydrogeochemical characterization for groundwater quality and risk assessment in part of central gangetic alluvium, India. Groundwater for Sustainable Development 25, 101108. doi:10.1016/j.gsd.2024.101108.

Guhathakurta, P., Rajeevan, M., Sikka, D.R., Tyagi, A., 2015. Observed changes in southwest monsoon rainfall over India during 1901–2011. The International Journal of Climatology 35(8), 1881–1898. doi:10.1002/joc.4095.

Gupta, R., Sharma, P.K., 2023. A review of groundwater-surface water interaction studies in India. Journal of Hydrology 621, 129592. doi:10.1016/j.jhydrol.2023.129592.

Lal, M., 2003. Global climate change: India's monsoon and its variability. Journal of Environmental Studies and Policy 6(1), 1–34. URL: https://www.researchgate.net/publication/281402625.

Li, P., Elumalai, V., 2025. Hydrogeology and the global significance of groundwater, in: Sustainable Groundwater and Environment: Challenges and Solutions. Springer Nature Switzerland, Cham, p. 1–20. doi:10.1007/978-3-031-82194-3_1.

Mukherjee, A., Saha, D., Harvey, C.F., Taylor, R.G., Ahmed, K.M., Bhanja, S.N., 2015. Groundwater systems of the Indian sub-continent. Journal of Hydrology: Regional Studies 4, 1–14. doi:10.1016/j.ejrh.2015.03.005.

Mukherjee, P., Singh, C.K., Mukherjee, S., 2012. Delineation of groundwater potential zones in arid region of India—a remote sensing and GIS approach. Water Resources Management 26, 2643–2672. doi:10.1007/s11269-012-0038-9.

Nair, A.S., Indu, J., 2021. Assessment of groundwater sustainability and identifying factors inducing groundwater depletion in India. Geophysical Research Letters 48(3), e2020GL087255. doi:10.1029/2020GL087255.

National Aquifer Mapping and Management Program (NAQUIM). Ministry of Water Resources, Government of India. URL: http://mowr.gov.in.

Panda, D.K., Ambast, S.K., Shamsudduha, M., 2021. Groundwater depletion in northern India: impacts of the sub-regional anthropogenic land-use, socio-politics and changing climate. Hydrological Processes 35(2). e14003. doi:10.1002/hyp.14003.

Pattanaik, D.R., Rajeevan, M., 2010. Variability of extreme rainfall events over India during southwest monsoon season. Meteorological Applications: A Journal of Forecasting, Practical Applications Training Techniques and Modelling 17(1), 88–104. doi:10.1002/met.164.

Rodell, M., Velicogna, I., Famiglietti, J.S., 2009. Satellite-based estimates of groundwater depletion in India. Nature 460(7258), 999–1002. doi:10.1038/nature08238.

Saha, D., Dwivedi, S.N., Ali, S., 2024. Research on groundwater science and management in India. Proceedings of the Indian National Science Academy 90(2), 468–481. doi:10.1007/s43538-024-00259-0.

Saha, D., Ray, R.K., 2018. Groundwater resources of India: potential, challenges and management, in: Groundwater Development and Management: Issues and Challenges in South Asia. Springer International Publishing, Cham, p. 19–42. doi:10.1007/978-3-319-75115-3_2.

Sahoo, S., Singha, C., Govind, A., Sharma, P., 2025. Review of aquifer storage and recovery opportunities and challenges in India. Environmental Earth Sciences 84(5), 122. doi:10.1007/s12665-025-12124-4.

Scanlon, B.R., Fakhreddine, S., Rateb, A., de Graaf, I., Famiglietti, J., Gleeson, T., Grafton, R.Q., Jobbagy, E., Kebede, S., Kolusu, S.R., Konikow, L.F., 2023. Global water resources and the role of groundwater in a resilient water future. Nature Reviews Earth & Environment 4(2), 87–101. doi:10.1038/s43017-022-00378-6.

Shaji, E., Santosh, M., Sarath, K.V., Prakash, P., Deepchand, V., Divya, B.V., 2021. Arsenic contamination of groundwater: a global synopsis with focus on the Indian Peninsula. Geoscience Frontiers 12(3), 101079. doi:10.1016/j.gsf.2020.08.015.

Shaji, E., Sarath, K.V., Santosh, M., Krishnaprasad, P.K., Arya, B.K., Babu, M.S., 2024. Fluoride contamination in groundwater: a global review of the status, processes, challenges, and remedial measures. Geoscience Frontiers 15(2), 101734. doi:10.1016/j.gsf.2023.101734.

Shaw, R., Luo, Y., Cheong, T.S., Abdul Halim, S., Chaturvedi, S., Hashizume, M., Insarov, G.E., Ishikawa, Y., Jafari, M., Kitoh, A., Pulhin, J., Singh, C., Vasant, K., Zhang, Z., 2022. Asia, in: Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B. (Eds.), Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge

University Press, Cambridge, UK and New York, NY, USA, p. 1457–1579. doi:10.1017/9781009325844.012.

Siebert, S., Burke, J., Faures, J.M., Frenken, K., Hoogeveen, J., Döll, P., Portmann, F.T., 2010. Groundwater use for irrigation–a global inventory. Hydrology and Earth System Sciences 14(10), 1863–1880. doi:10.5194/hess-14-1863-2010.

Singh, D.K., Singh, A.K., 2002. Groundwater situation in India: problems and perspective. International Journal of Water Resources Development 18(4), 563–580. doi:10.1080/0790062022000017400.

Singh, V.K., Pandey, H.K., Singh, S.K., Soni, P., 2023. Groundwater analysis using gravity recovery, climate experiment and google earth engine: Bundelkhand region, India. Physics and Chemistry of the Earth, Parts A/B/C 130, 103401. doi:10.1016/j.pce.2023.103401.

Swain, S., Taloor, A.K., Dhal, L., Sahoo, S., Al-Ansari, N., 2022. Impact of climate change on groundwater hydrology: a comprehensive review and current status of the Indian hydrogeology. Applied Water Science 12(6), 120. doi:10.1007/s13201-022-01652-0.

Taloor, A.K., Sharma, S., Suryakiran, S., Sharma, R., Sharma, M., 2024. Groundwater contamination and health risk assessment in Indian subcontinent: a geospatial approach. Current Opinion in Environmental Science & Health 39, 100555. doi:10.1016/j.coesh.2024.100555.

Yahaya, I., Li, Z., Zhou, J., Jiang, S., Su, B., Huang, J., Xu, R., Havea, P.H., Jiang, T., 2024. Estimations of potential evapotranspiration from CMIP6 multi-model ensemble over Africa. Atmospheric Research 300, 107255. doi:10.1016/j.atmosres.2024.107255.