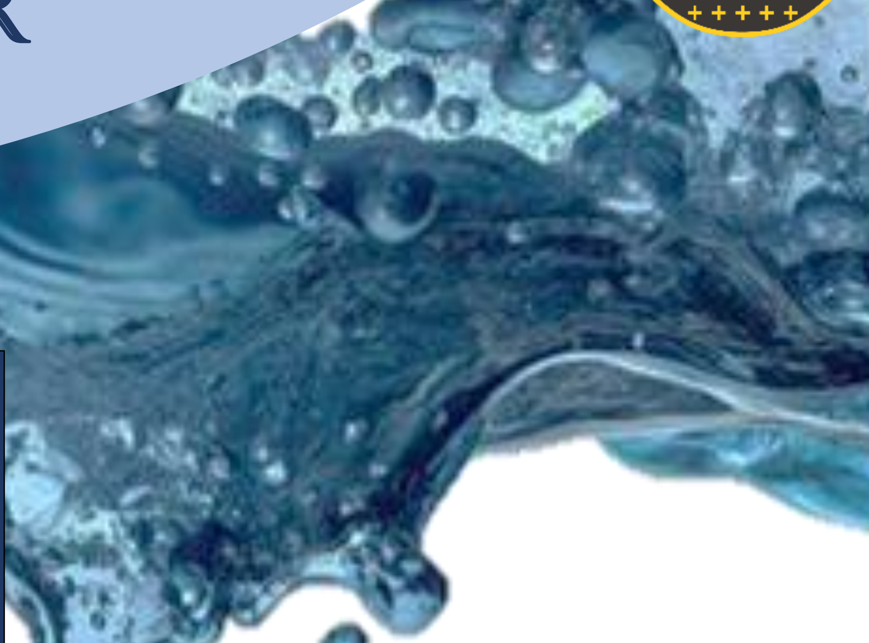
INC of IAH
Indian National Chapter
International Association of Hydrogeologists

NEWSLETTER

VOLUME 13 ISSUE 01

JUNE,2026



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Vice-President (Asia), IAH Council
President (INC -IAH),
Former Vice-Chancellor,
Chhatrapati Shivaji University, Navi Mumbai
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Dear Members and Friends of IAH,

Warm greetings from the Indian National Chapter of the International Association of Hydrogeologists.

As we approach the middle of 2026, I am pleased to connect with our esteemed members, colleagues, and groundwater professionals from India and across the world through this quarterly edition of our E-Newsletter.

During the past quarter, the Indian National Chapter has continued its efforts to promote groundwater science, capacity building, professional networking, and stakeholder engagement evident from the organisation of a workshop on geophysical applications in groundwater exploration; organisation of a national seminar, honouring the veterans, awards distribution,celebration of world water day (week)partnering with Australia India Water Centre (AIWC), Sydney and many more despite losing some valuable time in tackling the negative narratives.

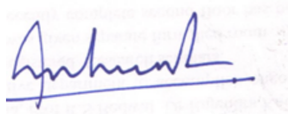
As Vice President (Asia) of IAH, I am also exploring the possibility of organizing an Asian Groundwater Conference during early 2027 with the objectives of further strengthening cooperation among Asian countries, facilitate the exchange of experiences, and promote collaborative solutions to common groundwater challenges. I welcome suggestions and expressions of interest from our colleagues from India and across the region.

I am also delighted to inform you all that the Indian National Chapter of IAH, in collaboration with the National Institute of Hydrology (NIH), Roorkee and the MAR Commission of IAH will host the 13th International Symposium on Managed Aquifer Recharge (ISMAR-13) in India during October 2027. This prestigious international event will bring together leading experts, researchers, practitioners, and policymakers from around the world to discuss advances and innovations in managed aquifer recharge and sustainable groundwater management. We look forward to your active participation and support in making ISMAR-13 a landmark event.

I shall personally be happy to know how many of you are participating in 53rd IAH Congress in Budapest.

Let us continue working together to promote science-based groundwater management, enhance national and international cooperation, promote opportunities for youngsters and secure groundwater resources for future generations.

With best wishes and warm regards.



A.K.Sinha
President

Secretary's Message

Dr.Sudhanshu Shekhar

Secretary(INC of IAH),
Former Scientist, Central Ground Water Board,
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Accredited Ground Water Professional and Certified Water Auditor
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Dear Esteemed Members of INC-IAH,

It gives me immense pleasure to present the 13th-Year Edition (Vol. 1) of the E-Newsletter of the Indian National Chapter of the International Association of Hydrogeologists (INC-IAH). This issue is particularly significant for me as it is the first newsletter published during my tenure as Secretary of INC-IAH for the period 2026–2028.

At the outset, I extend my heartfelt congratulations to the newly elected Governing Body members of INC-IAH for the term 2026–2028. I am confident that under the leadership of Prof. (Dr.) A. K. Sinha, President, and with the support of all office bearers and members, INC-IAH will continue to promote excellence in hydrogeology and sustainable groundwater management.

The year 2026 has begun on a positive note for our Chapter. A major achievement was the successful organization of the National Seminar on "Water Management for Sustainable Groundwater Use: A Journey from the Vedic Age to the Modern Age," jointly organized by Maharshi Yogi Vedic Vishwavidyalaya and INC-IAH at Katni in March 2026. The seminar brought together over one hundred scientists, academicians, professionals, researchers, and students, providing a valuable platform for the exchange of knowledge and experiences on groundwater issues.The seminar was preceded by a workshop-cum-training programme on "Application of Geophysics in Groundwater Exploration," organized by Dr. S. C. Singh, Prof. B. S. Chowdhary, and Prof. B. Venkateswar Rao. The programme enhanced participants' understanding of modern geophysical techniques and their applications in groundwater exploration and management.

A memorable feature of the event was the felicitation of distinguished Veteran Hydrogeologists for their lifelong contributions to groundwater science and management in India. I also congratulate the recipients of the INC-IAH Awards 2024, which recognize outstanding achievements in groundwater research, education, and management.

This issue includes regular features such as groundwater news from India and abroad, reports on INC-IAH activities, awards and recognitions, forthcoming events, and technical articles. I hope these contributions will keep members informed and encourage greater participation in scientific and professional activities.

I sincerely thank the Editorial Team, Ms. Chirashree Mohanty and Ms. Suhani Srujanika, along with all contributors, Governing Body members, authors, and well-wishers whose support made this newsletter possible. I invite members to actively participate in INC-IAH programmes and contribute articles and technical notes for future editions.

I also appeal to hydrogeologists, groundwater professionals, researchers, academicians, and students to strengthen the INC-IAH fraternity through active participation and membership for the advancement of groundwater science and sustainable water resources management.

With best wishes for your continued success and valuable contributions to groundwater science and management.

Dr. Sudhanshu Shekhar
Secretary, INC-IAH

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Dear Readers,

It is indeed a great honour to serve as the editors of the newsletter for this edition of the INC-IAH newsletter, and it is an immense pleasure to bring out this thirteenth-year edition (Volume 13, Issue 1) for June 2026. This issue recounts the rich array of activities that have shaped the Chapter's work over the past several months, from the National Seminar held in Jabalpur to the felicitation of our veteran hydrogeologists, alongside updates on national groundwater policy, recent headlines, and forthcoming international events.

This edition opens with an overview of the Government of India's groundwater management initiatives from the Jal Shakti Abhiyan and Atal Bhujal Yojana to NAQUIM 2.0 and Mission Amrit Sarovar, situating the Chapter's work within the larger national effort to secure India's water future. It also carries a curated roundup of major groundwater headlines from across the country between January and May 2026, capturing both the achievements and the mounting challenges.

We are pleased to report extensively on the INC-IAH National Seminar on "Water Management for Sustainable Groundwater Use - A Journey from the Vedic Age to Modern Age," jointly organised with Maharshi Mahesh Yogi Vedic Vishwavidyalaya at Katni in March 2026, which brought together more than a hundred scientists, scholars, and students.

On the technical front, this volume carries three substantive articles: a review of groundwater systems and their environmental challenges by Mr. Binay Prakash Panigrahy (IIT-ISM Dhanbad); a study on the impact of rainfall variability on groundwater recharge in semi-arid regions by Mr. Valluru Naga Venkatanadh and colleagues from the University of Agricultural Sciences, Raichur; and an article on microplastic contamination in Indian cities, co-authored by us. We hope these contributions offer readers both scientific depth and practical relevance.

Last but not least, we would like to thank INC-IAH President Prof. A. K. Sinha, Vice President Prof. Bhagwan Singh Chaudhary, Secretary Dr. Sudhanshu Shekhar, and all Executive Committee members for their continued support and guidance throughout the preparation of this edition.Putting together this edition has been a genuinely collaborative effort, and we are grateful to every contributor who took the time to share their research, field experience, and insights with the wider INC-IAH community.

We sincerely request all members, particularly young hydrogeologists, to come forward and add their contributions to make this quarterly newsletter more informative and readable for a wide audience. This is an open newsletter; members may circulate it to an individual or group for wider publicity. This is the only way to grow and make INC-IAH a stronger professional place.

Mrs. Chirashree Mohanty &Ms. Suhani Srujanika

Editors, INC-IAH Newsletter, June 2026

Major Groundwater Headlines in India

Coverage period: January 2026 to May 2026

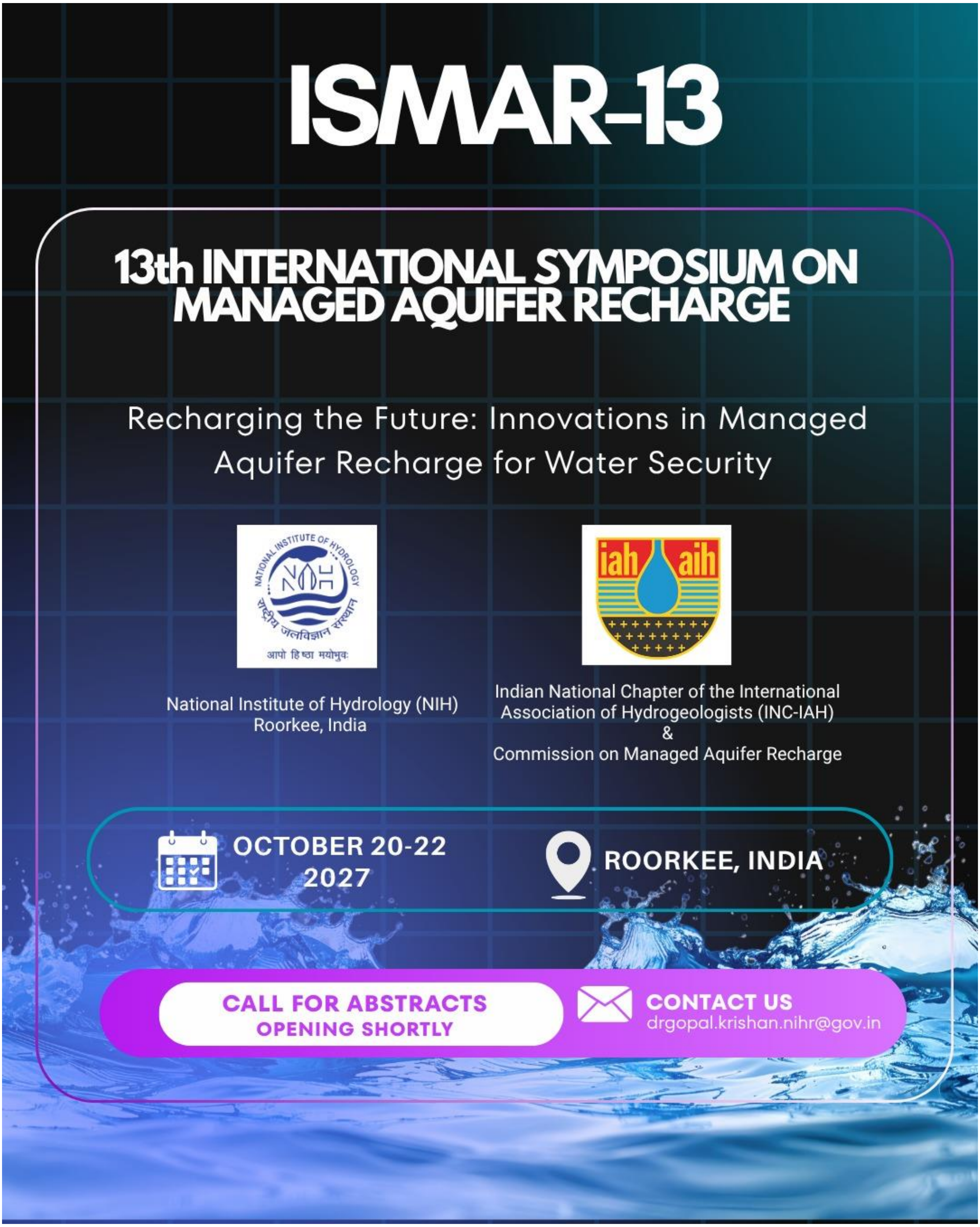
Month	Headline	Key Point	Links
January 2026	**Government highlighted national groundwater management measures**	Ministry of Jal Shakti/PIB stated that India has **43,228 groundwater monitoring stations** and is using CGWB monitoring, Atal Bhujal Yojana, Jal Shakti Abhiyan, recharge works and revival of defunct borewells for groundwater management.	Link
January 2026	**Hyderabad groundwater stress warning before peak summer**	Reports from Hyderabad warned that some mandals had improved after monsoon, but urban groundwater remained under pressure before summer.	Link
January 2026	**Ghaziabad recharge drive slowed by funding shortage**	Groundwater recharge works in Ghaziabad were affected by shortage of funds; Loni and Rajapur remained stressed/over-exploited areas.	Link
January 2026	**Telangana warned of possible "zero day" risk by 2034**	A study-based report warned that Telangana's groundwater use was approaching critical levels, with risk of serious depletion if present agricultural practices continue.	Link
February 2026	**Government gave official groundwater resource numbers**	PIB reported 2025 national groundwater assessment figures: 448.52 BCM annual recharge, 407.75 BCM extractable resource, and 247.22 BCM extraction.	Link
February 2026	**CGWB issued/reminded remedial measures for groundwater contamination**	CGWB measures include advisories, NAQUIM reports, training, public interaction, and techniques for arsenic- and fluoride-safe wells.	Link
February 2026	**CGWB groundwater data dissemination workshops continued**	CGWB organised state/district-level groundwater data and aquifer mapping workshops, including in Kohima and other regions.	Link
March 2026	**Punjab Malwa region: depletion plus toxic contamination**	Reports highlighted a dual crisis in Punjab's Malwa region: falling water table and toxic elements such as uranium and arsenic in groundwater.	LInk
March 2026	**Groundwater crisis framed as national urban and rural emergency**	India Today described the crisis as a combination of sinking cities, over-extraction, poisoned groundwater and aquifer stress.	Link

	Headline	Key point	Links
March 2026	**Rajasthan fluoride and uranium contamination became major public-health issue**	Reports linked January 2026 CGWB quality findings to fluoride contamination across over 30 Rajasthan districts and uranium levels above safety limits in several locations.	Link
April 2026	**Groundwater governance and recharge actions reviewed**	SANDRP reviewed government actions on recharge and regulation, including injection borewells, groundwater governance gaps and recharge initiatives.	Link
April 2026	**Athani, Karnataka: proposal for 1,000 injection borewells**	Athani proposed installing 1,000 injection borewells across 18 villages to recharge aquifers using canal water, rainwater and surface runoff.	Link
May 2026	**Maharashtra: 70 talukas below long-term groundwater average**	GSDA assessment found groundwater levels in 70 talukas below long-term average in March, with seven talukas entering stress category.	Link
May 2026	**Mumbai: illegal groundwater extraction despite aquifers being called "safe"**	Mumbai aquifers were reportedly certified "safe," but the government lacked data on illegal borewells and actual groundwater extraction.	Link
May 2026	**Hyderabad: illegal borewell water trade in Osmannagar and Tellapur**	Unauthorised borewell operators were reported to be extracting and selling groundwater, worsening local scarcity.	Link
May 2026	**Karnataka: industrial borewells rose sharply**	Karnataka recorded a 10.3% increase in industrial borewells in 2025, raising concern over industrial extraction and weak monitoring.	Link
May 2026	**Indore: residents forced to use contaminated groundwater**	Palda residents in Indore reportedly depended on contaminated groundwater because of severe water shortage.	Link
May 2026	**Rajasthan launched statewide water conservation campaign**	Rajasthan launched Vande Ganga Jal Sanrakshan Jan Abhiyan 2026 to improve water-holding capacity before monsoon; the state depends heavily on groundwater for drinking water and irrigation.	Link
May 2026	**PFAS/"forever chemical" concern linked to Maharashtra plant**	Protests arose over PFAS production and the relocation of equipment from an Italian factory associated with aquifer contamination, raising concern over chemical regulation in India.	Link

Forthcoming International Seminar and Conferences

Sl No	Topic	Date	Venue
1	International Conference on Hydraulics, Water Resources, River and Coastal Engineering (HYDRO International 2026)	December 17–19, 2026	IIT Indore, Madhya Pradesh
2	International Conference on Isotope Hydrology and Tracer Applications in Water Science (ICIHTAWS-26)	August 1st, 2026	Pondicherry, India Hybrid Mode
3	International Conference on Sustainable Drainage Systems and Urban Water Management	August 1st 2026	Visakhapatnam, India, Hyderabad, India
4	International Conference on Water Cycle Science and Global Change Dynamics	August 16 2026	Hyderabad, India
5	International Conference on Hydro geophysics and Aquifer Characterization	September 13 2026	Visakhapatnam, India
6	IAH 2026: 53rd World Groundwater Congress monitoring, and protection of global groundwater resources	September 14–18, 2026	Budapest, Hungary
7	International Conference on Urban Groundwater Recharge and Aquifer Vulnerability	October 4th, 2026	Goa
8	2026 UN Water Conference	December 8–10, 2026	United Arab Emirates (UAE)
9	Annual SADC Groundwater Conference, Accelerating oundwater Resilience for a Water-Secure Future.	November 18–20, 2026	Dar Es Salaam, Tanzania

Sl No	Topic	Date	Venue
10	**International Conference on Sustainable Groundwater Management in Arid Zones (ICSGMAZ-26)**	**October 15–16, 2026**	**Dubai, UAE**
11	**54th International Association of Hydrogeologists (IAH) World Groundwater Congress will take place in from. Themed "Groundwater: A Tool for Peace"**	**September 20-24, 2027**	**Mexico**
12	**11th International Waters Conference (IWC11) transboundary basins - GEF portfolio - ocean SDGs - knowledge exchange GEF IW:LEARN**	**19 to 22 October 2026**	**Bali, Indonesia**
13	**7th International Summer School on MAR**	**31.08. – 11.09.2026**	**MARISS, Dresden**


ISMAR-13
13th INTERNATIONAL SYMPOSIUM ON MANAGED AQUIFER RECHARGE
Recharging the Future: Innovations in Managed Aquifer Recharge for Water Security
NATIONAL INSTITUTE OF HYDROLOGY
राष्ट्रीय जलविज्ञान संस्थान
National Institute of Hydrology (NIH)
Roorkee, India
iah aih
Indian National Chapter of the International Association of Hydrogeologists (INC-IAH)
&
Commission on Managed Aquifer Recharge
OCTOBER 20-22
2027
ROORKEE, INDIA
CALL FOR ABSTRACTS
OPENING SHORTLY
CONTACT US
drgopal.krishan.nihr@gov.in

9th India International Water Week 2026

22-26 September, 2026

Bharat Mandapam, New Delhi

THEME: CLIMATE RESILIENT WATER MANAGEMENT

September 22-26, 2026 | CONVENTION CENTER & HALL NO. 14, BHARAT MANDAPAM, NEW DELHI

We invite you to be a part of the 9th India International Water Week 2026.

Conceptualised in 2012, the event is organised biennially by the Ministry of Jai Shakti, Government of India. It serves as the largest international platform for dialogue, innovation and cooperation in the water sector. This year it focuses on Climate Resilient Water Management.

The Second International WASH Conference 2026 will also be a part of this year's edition.

The event brings experts, researchers, innovators and practitioners together to strengthen water security, resilience, sustainability, and inclusive development, supported by innovation, financing, and inclusive governance.

DELEGATES

5,000+ Expected

EXHIBITION

7,000 sq.m.

Bare Space:
INR 16,000/sq.m. + GST
USD 600/sq.m.

Shell Scheme:
INR 20,000/sq.m. + GST
USD 750/sq.m.

CALL FOR PAPERS

We invite researchers, practitioners and water professionals to submit papers across the following sub-themes:

- Inclusive and Equitable Water Governance
- Cooperation for Optimal Use of Water Resources
- Technology and Community for Water Security
- Farming Water in Climate-Related Risks
- Innovative Financing Models for Water Infrastructure
- Sustainable Water Resource Management
- Water for People and Planet

Last date for Abstract submission: 10 May 2026

Approval of Abstract by: 15 May 2026

Last date for Full Length Paper submission: 25 May 2026

Approval of Full Length Paper by: 05 June 2026

1. Election to Governing Body of Indian Chapter of IAH (INC of IAH) For 2026-28

Subsequent to the completion of the election process as defined in the constitution of INC of IAH, the following persons were elected **UNOPPOSED** to the INC IAH Governing Body for the Period 2026-2028 as announced by the Election Officer, Sri Y. B. Kaushik.

President
Dr.A. K Sinha
Vice President (Asia),IAH Council
Former Vice Chancellor,Chhatrapati Shivaji Maharaj University, Mumbai, Maharashtra
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VicePresident
Prof. Bhagwan Singh Chaudhary
Chairman and Professor, Dept. of Geophysics,Kurukshetra University, Kurukshetra
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Secretary
Dr. Sudhanshu Shekhar
Former Scientist, Central Ground Water Board, Ministry of Jal Shakti, Govt of India.
Accredited Ground Water Professional and Certified Water Auditor
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Treasurer
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2. Workshop and National Seminar (15th to 17th March 2026)

2.1.The two-day national seminar was preceded by a one-day workshop cum training program on “Application of Geophysics in Groundwater Exploration” where in 24 students, research scholars and young career scientist and academician participated. The chief resource person Dr Subhash Singh conducted the classroom and field-based program who was duly assisted by Prof B. Venkateshwar Rao and Prof B.S Chaudhary.

Dr. Subhash Singh demonstrating the resistivity survey to the deleg

2.2. INC-IAH Seminar on Water Management for the Sustainable Ground Water Use-A journey from Vedic Age to Modern Age was successfully organised jointly by Maharishi Yogi Vedic Vishwavidyalaya (MMYVV), Jabalpur, India, and Indian National Chapter of IAH (INC of IAH) at MMYVV, Katni on 16-17th March 2026. Wherein more than 100 young and senior scientists from various domains engaged in the study of water, particularly of groundwater participated.

2.3 Facilitation of the Veteran Hydrogeologist of India for 2026

The following distinguished Hydrogeologists were felicitated for 2026

Sri Shambhu Nath

Superintending Hydrogeologists (Retired) CGWB, GOI

Professor A. D. Sawant

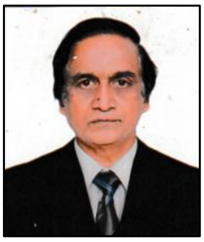
Former Vice-Chancellor, UOR, Jaipur and Pro-VC Mumbai University Mumbai.

Shri Subhojyoti Das

Former Regional Director, CGWB

Professor D.C Singhal

Former President, INC of IAH and Former Professor IIT Roorkee



Sri Chunduri Satyanarayna

Former Chief Hydrogeologist, REC, Govt of India

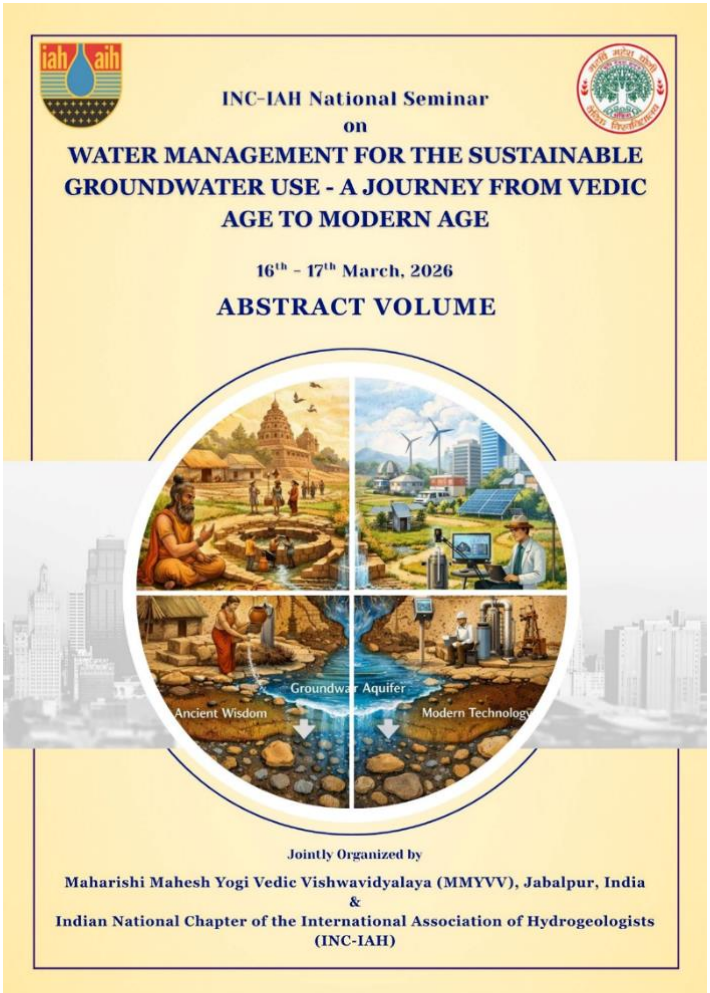
2.4. INC-IAH National Seminar Abstract Volume: A Confluence of Vedic Knowledge and Modern Hydrogeology

The Abstract Volume released ahead of the INC-IAH National Seminar (16–17 March 2026, Jabalpur) offers a revealing snapshot of where Indian groundwater science stands today — and it is a more interesting document than its modest title suggests. Spanning over 100 abstracts from CGWB scientists, IIT faculty, state groundwater departments, and university researchers, the volume is organised around a deliberately unusual premise: that the path to sustainable groundwater management runs through both Vedic textual scholarship and contemporary geophysics.

It brings together over 100 papers from researchers, policymakers, and practitioners across the country, reflecting a distinctly Indian approach to groundwater science — one that places ancient textual knowledge alongside contemporary geophysical and computational methods. Contributions range from electrical resistivity tomography and GIS-based aquifer mapping to machine learning applications in groundwater forecasting, alongside a substantial body of work examining water management principles described in the Vedas, the Arthashastra, and Varahamihira's Brihat Samhita. Keynote contributions include Prof. Abhijit Mukherjee's (IIT Kharagpur) work connecting tectonics to geogenic groundwater contamination and addresses from senior CGWB officials and INC-IAH leadership on national groundwater governance.

The volume is, in effect, a working argument that India's groundwater crisis cannot be solved by imported technical solutions alone — that locally evolved knowledge systems, going back millennia, contain genuine hydrological insight worth taking seriously alongside ERT surveys and machine learning models. Whether or not one is persuaded by every Vedic-science parallel drawn in its pages, the volume

captures a seminar genuinely trying to bridge two ways of knowing water, at a moment when India's aquifers can least



NATIONAL SEMINAR ON
WATER MANAGEMENT FOR THE SUSTAINABLE
GROUNDWATER USE - A JOURNEY FROM VEDIC AGE TO MODERN AGE
(16 - 17 MARCH 2026 AT JABALPUR, MADHYA PRADESH, INDIA)

COMMITTEE MEMBERS FOR NATIONAL SEMINAR

PATRON

Prof. (Dr) P.K.Varma,
Vice Chancellor, Maharshi Mahesh Yogi Vedic Vishwavidyalaya, Katni (MP)
Prof. A. K. Sinha,
Vice-President IAH Asia and President INC-IAH

CONVENERS

Dr. J.P. Shukla,
Maharshi Mahesh Yogi Vedic Vishwavidyalaya, Katni (MP)
Dr. Anadi Gayen
Central Groundwater Board
Organising Secretary
Dr Ankit Kailashi Rathod
Maharshi Mahesh Yogi Vedic Vishwavidyalaya, Katni (MP)
Prof. B.S Chaudhary
Secretary INC-IAH & Chairman, Dept. of Geophysics, KU, Kurukshetra

COMMITTEES

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Dr. Teodara Szocs, IAH President
Prof. A. D. Sawant, Former VC, UOUR, Jaipur
Prof. Basant Maheshwari, West Australian University
Dr. IAN Dave, Executive Manager, IAH
Sri Sushil Gupta, Former Chairman, CGWB
Prof. Bijay Singh, Sikkim Skill University, Sikkim
Dr. T. B. N. Singh, Member, CGWB
Dr. Prakash Kumar, Director, NGRI, Hyderabad
Dr S. K. Singh, Director, NIO, Goa

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Ex-Advisor, CAIRN INDIA
Dr. Sudhanshu Shekhar, CGWB
Prof. Bhavana Umrikar, SPPU, Pune
Prof. Seemant Sharma, MMYVV, Katni
Dr. Ashwani Kumar Tiwari, SES, JNU
Dr. Chirashree Mohanty, CGWB, Bhubaneswar
Ritweek Dubey, MMYVV, Katni
Rudra Pradhan, CESS, Trivendrum
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Dr. R. P. Kushwaha, CSMU, Mumbai

afford either approach working in isolation.

2.5 INC-IAH Awards 2024

INC-IAH Awards- 2024 for different categories were announced, which were given during the Seminar on 16th March 2026

Lifetime Achievement Award

Sri Anand Kumar Agarwal
Former Chairman, CGWB, GOI

Ground Water Excellence Award

Professor (Dr) Abhijit Mukherjee
Professor, IIT, Kharagpur

Young Scientist Award

Dr. Chinmay Dongre
Asst. Professor, Dept. of Geology, M.S. University, Vadodara

Best Paper Award (Female category)

Dr. Seema R Basarikatti
KLS VRD Institute of Technology,

Best Paper Award (Male category)

Dr. Aditya Shekhar
MNNIT, Allahabad

Best Ph.D. Thesis Award

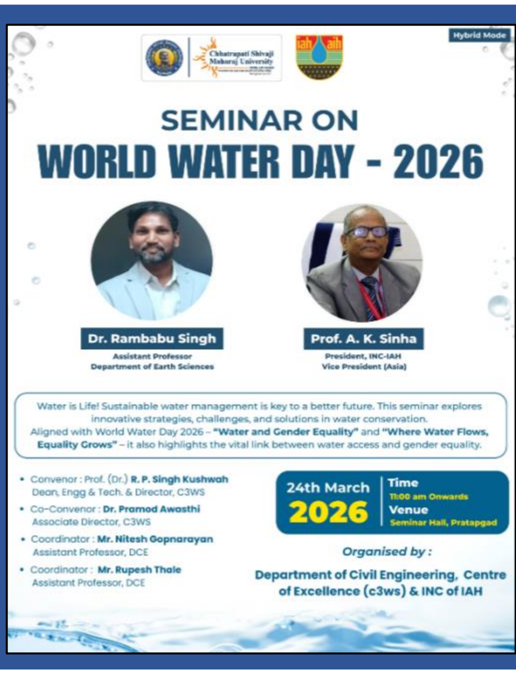
Dr. Vipin Garg
Central University of Rajasthan,

Best Post-Graduate Dissertation Award

Mr. Amit Sharma
Jammu University, Jammu

3. INC-IAH World Water Day Celebration 2026.

The Indian Chapter of IAH in association with Chhatrapati Shivaji Maharaj University Navi Mumbai, Maharashtra, celebrated the world water day by organising one-day Seminar in hybrid mode on 24 March World Water Day 2026 theme. The main speakers were Prof. A. K. Sinha, President INC IAH; Dr. Rambabu Singh, IIT Mumbai; Prof. R. P. Singh Kushwaha.



Groundwater Systems and Their Environmental Challenges: A Review

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Abstract

Groundwater is one of the world's most important freshwater resources, representing approximately 30% of the world's freshwater reserves, and supplying more than two billion people with their primary source of drinking water (UNESCO-IHP, 2022). This paper summarizes the dynamics of groundwater systems including aquifer types, recharge methods and hydrogeological processes. We discuss the growing environmental issues affecting these systems such as land-use change, anthropogenic contamination, overexploitation and hydrological change driven by climate change (Gleeson et al., 2020; Taylor et al., 2013). The interaction between groundwater and surface water ecosystems is discussed and an analysis of geogenic pollutants such as arsenic and fluoride that pose public health threats in many regions is presented (Bhattacharya et al., 2007; Rahman et al., 2009). The management frameworks of integrated water resources management (IWRM), managed aquifer recharge (MAR) and emerging monitoring technologies are critically reviewed. The review highlights the need for adaptive, interdisciplinary approaches to ensure groundwater sustainability in an era of accelerating global change.

Keywords: *groundwater, aquifer systems, contamination, overexploitation, climate change, hydrogeology, water management, environmental sustainability*

1. Introduction

Aquifers are geological structures that store groundwater, which is the planet's largest accessible source of liquid freshwater (Alley et al., 2002). Because groundwater is hidden beneath the Earth's surface, it is more difficult to measure and manage than surface water, which is visible and relatively easy to monitor (Foster & Chilton, 2003). Groundwater is now essential to human civilization, food security, and ecological integrity as freshwater demand rises due to urbanization, agricultural intensification, and worldwide population expansion.

Groundwater is important for reasons far beyond human use. It maintains soil moisture, which is essential for agriculture, supports wetland habitats, maintains baseflow in rivers and streams, and controls ground subsidence (Sophocleous, 2010). Groundwater is the sole dependable source of water during dry seasons in many arid and semi-arid areas (Siebert et al., 2010). Despite its significance, a combination of anthropogenic and natural stressors puts groundwater systems under unprecedented strain globally (Famiglietti, 2014; Gleeson et al., 2012).

The goal of this paper is to present a thorough synthesis of the environmental concerns associated with groundwater system science. It is structured to first determine the hydrogeological and physical underpinnings of groundwater systems, then look at major environmental risks, and finally evaluate management and policy solutions (Gorelick & Zheng, 2015). Educating scientists, decision-makers, and practitioners involved in the sustainable management of this vital resource is the aim.

2. Fundamentals of Groundwater Systems

2.1 Definition and Global Occurrence

Water found in the saturated zone of the Earth's subsurface, where all of the pore spaces in rock, soil, and sediment are fully filled with water, is referred to as groundwater. In unconfined systems, the water table is the upper limit of the saturated zone (Alley et al., 2002). Only a small portion of the estimated 10.6 million km³ of groundwater stored worldwide circulates on timescales relevant to humans (Gleeson et al., 2020). The remainder is made up of fossil water, or old reserves left behind by previous climatic conditions. These reserves do not refill on human timescales, which presents significant difficulties for areas that rely on these non-renewable stocks.

2.2 Aquifer Types and Classification

Aquifers are geological formations capable of storing and transmitting significant volumes of water (Foster & Chilton, 2003). Based on their geological and hydraulic characteristics they are broadly classified into four types:

- Unconfined (Phreatic) Aquifers:These are directly replenished by rainwater seeping through the unsaturated zone and are only limited by the water table above. According to Alley et al. (2002), they are extremely susceptible to surface contamination.

- Confined Aquifers: These aquifers are under pressure higher than atmospheric, sandwiched between impermeable layers (aquitards). When water rises above the aquifer top in boreholes that penetrate confined aquifers, artesian conditions can arise if there is enough pressure (Custodio, 2002).

- Semi-Confined (Leaky) Aquifers: Surrounded by aquitards that allow gradual vertical flow. Regional water budgets may be significantly impacted by leaks between aquifer layers.

- Perched Aquifers: An unsaturated zone separates local, isolated groundwater bodies from the main water table. They are frequently seasonal and yield-limited.

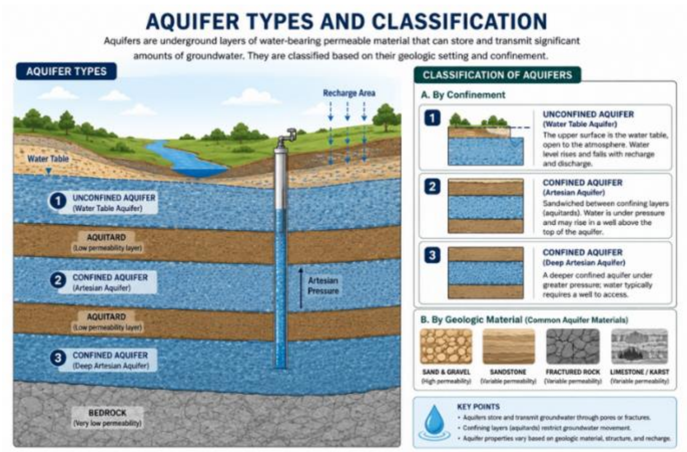

Fig 1: Aquifer Types and Classification (Groundwater by C. W. Fetter)

2.3 Recharge Mechanisms and Water Balance

Aquifer recharge — the process by which water infiltrates the subsurface to replenish groundwater stores — is a fundamental control on system sustainability (Scanlon et al., 2007). Recharge pathways include direct infiltration through the unsaturated zone, focused recharge via streambeds and losing rivers, and indirect recharge from irrigation return flows. The rate and spatial distribution of recharge depend on precipitation intensity and frequency, soil type and cover, vegetation, topography, and the depth and properties of the unsaturated zone (Taylor et al., 2013). In many regions, recharge is highly episodic, concentrated during intense rainfall events or seasonal floods, with substantial inter-annual variability (Döll et al., 2012).

2.4 Groundwater Flow Systems

Darcy's Law, which links flux to hydraulic gradient and hydraulic conductivity, controls groundwater flow (Alley et al., 2002). Flow systems are nested hierarchically at the landscape scale: regional flow systems travel across entire basins, sometimes over hundreds of kilometers; local flow systems move between nearby topographic highs and lows; and intermediate systems link recharge areas to more distant discharge zones. With significant ramifications for water chemistry, vulnerability, and management, these nested systems have unique residence times ranging from days to millennia (Foster & Chilton, 2003; Gleeson et al., 2020).

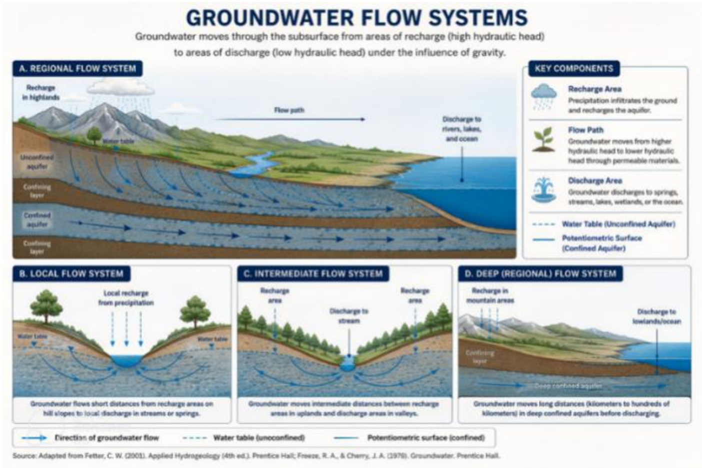

Fig 2: Groundwater Flow Systems

3. Groundwater–Surface Water Interactions

Groundwater and surface water are connected within a dynamic continuum; the hydrological cycle fails to make a clear distinctionbetween the two (Alley et al., 2002). During dry spells, groundwater discharge maintains aquatic habitats and water quality by sustaining baseflow in streams and rivers (Sophocleous, 2010). On the other hand, through floodplain inundation and streambed infiltration, surface water replenishes aquifers. Shallow groundwater supports biological production in riparian zones, which are crucial interfaces between terrestrial and aquatic habitats.

Phreatophytic vegetation, springs, wetlands, and hypogene habitats are examples of groundwater-dependent ecosystems (GDEs) (Gleeson et al., 2020). These habitats are particularly vulnerable to variations in groundwater quality and level. The saturated sediments beneath and next to streambeds, which allow surface water and groundwater to mingle, are known as the hyporheic zone. They are crucial for the decomposition of organic matter, the cycling of nutrients, and the habitats for specialized invertebrate groups (Foster & Chilton, 2003). Significant ecological harm may result from disrupting these relationships through groundwater abstraction or contamination (Taylor et al., 2013).

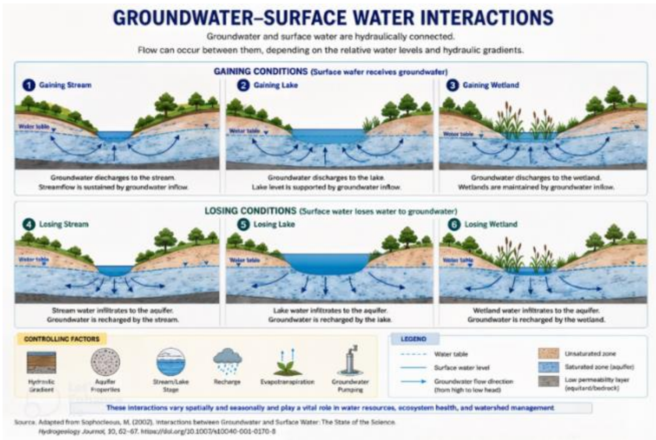

Fig 3: Groundwater–Surface Water Interactions

4. Environmental Challenges Facing Groundwater Systems

4.1 Overexploitation and Aquifer Depletion

Arguably, the most widespread and significant issue facing groundwater systems worldwide is groundwater overexploitation, or the continuous withdrawal of water at rates higher than natural recharge (Custodio, 2002; Famiglietti, 2014). About 70% of groundwater withdrawals worldwide are used for agricultural irrigation, with the majority of the remaining water being used for municipal and industrial purposes (Siebert et al., 2010). Overexploitation has a variety of negative effects that are frequently permanent.

1. Declining water table levels, increasing pumping costs and depths, and eventual well failure (Wada et al., 2010).

2. Land subsidence resulting from the compaction of aquifer materials as pore water pressure decreases — already causing serious infrastructure damage in cities such as Jakarta, Mexico City, and Shanghai (Konikow, 2011).

3. Saltwater intrusion into coastal aquifers as hydraulic gradients reverse under heavy pumping (Werner et al., 2013).

4. Irreversible loss of aquifer storage capacity due to inelastic compaction of fine-grained sediments (Custodio, 2002).

5. The North China Plain aquifer system, the Indus Basin in South Asia, and the High Plains (Ogallala) Aquifer in the United States are notable instances of overexploited systems (Sophocleous, 2010). In significant agricultural areas, groundwater storage is being depleted at rates of tens to hundreds of cubic kilometers annually, according to GRACE satellite gravity measurements (Famiglietti, 2014; Wada et al., 2010; Dỹ et al., 2012).

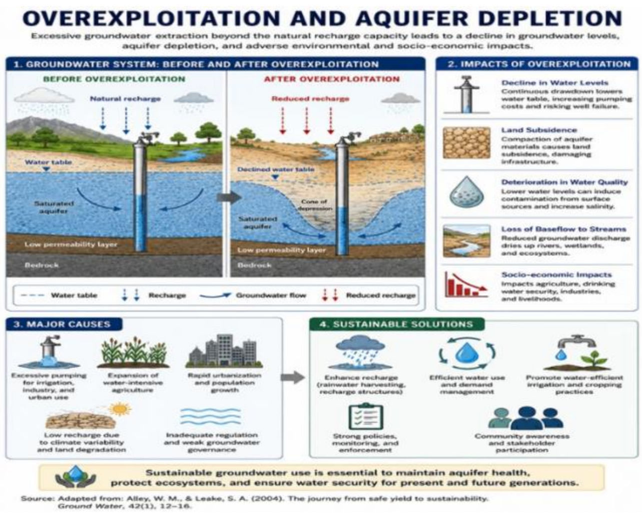

Fig 4: Overexploitation and Aquifer Depletion

4.2 Anthropogenic Contamination

Human activities introduce a broad spectrum of contaminants into groundwater systems, often with long-lasting consequences (Foster & Chilton, 2003). The subsurface environment, while providing some natural attenuation capacity, is vulnerable to numerous pollutant classes that infiltrate from the land surface.

4.2.1 Agricultural Pollutants

Nitrate leaching from synthetic fertilisers and animal manure is the most widespread agricultural groundwater contaminant globally (Scanlon et al., 2007). Nitrate concentrations exceeding the WHO guideline of 50 mg/L NO_3 are documented in aquifers across Europe, North America, and Asia. Pesticides, herbicides, and their metabolites — including atrazine, glyphosate, and chlorpyrifos — are detected in groundwater at varying concentrations. Veterinary pharmaceuticals and hormones introduced through manure application represent an emerging concern, with evidence of endocrine disruption at low concentrations (Foster & Chilton, 2003).

4.2.2 Industrial and Urban Contamination

Industrial activities generate diverse groundwater contaminants (Foster & Chilton, 2003). Chlorinated solvents — particularly tetrachloroethylene (PCE) and trichloroethylene (TCE) — are dense non-aqueous phase liquids (DNAPLs) that sink through aquifers and form persistent plumes extremely difficult to remediate. Heavy metals from mining operations, smelters, and industrial effluent include lead, cadmium, chromium, and zinc. Petroleum hydrocarbons from fuel spills and leaking underground storage tanks constitute light non-aqueous phase liquids (LNAPLs). Per- and polyfluoroalkyl substances (PFAS) — persistent synthetic chemicals used in firefighting foams and industrial processes — have emerged as a critical concern due to their extreme persistence and association with adverse health effects at very low concentrations (Gleeson et al., 2020).

4.2.3 Municipal and Domestic Sources

Improperly sited or maintained landfills generate leachate containing dissolved organic matter, heavy metals, and synthetic chemicals (Foster & Chilton, 2003). Septic systems and pit latrines in unserved communities introduce pathogens — including bacteria, viruses, and protozoa — as well as nitrate and pharmaceuticals. Leaking sewer infrastructure contaminates aquifers in urban areas, contributing to complex mixtures of contaminants in peri-urban groundwater (UNESCO-IHP, 2022).

4.3 Geogenic Contamination

Not all groundwater quality problems are of human origin. Naturally occurring geochemical processes release toxic elements into groundwater in many parts of the world, posing serious public health threats (Bhattacharya et al., 2007).

- Arsenic: The Bangladesh and West Bengal arsenic crisis is the largest mass poisoning in human history, affecting tens of millions of people drinking from shallow alluvial aquifers (Rahman et al., 2009). Arsenic mobilisation occurs under reducing conditions through the reductive dissolution of iron oxyhydroxide minerals. High-arsenic groundwaters are also documented in the Mekong delta, China's Huai River basin, and parts of South America and the USA (Bhattacharya et al., 2007).

- Fluoride: Elevated fluoride concentrations in groundwater — often from the weathering of fluoride-bearing minerals in crystalline and volcanic rocks — affect over 200 million people, primarily in Africa, India, and China, causing dental and skeletal fluorosis (Pandith Madhnure et al., 2015).

- Other geogenic contaminants include uranium (from granitic terrains), manganese, radon, iodine, and saline/brackish intrusion from evaporite dissolution (Bhattacharya et al., 2007).

4.4 Climate Change Impacts

Climate change is restructuring the hydrological cycle in ways that have profound implications for groundwater systems (Taylor et al., 2013). The pathways of impact are multiple and interacting:

- Recharge alteration: Changes in precipitation patterns, intensity, and seasonality affect recharge rates. In many regions, projections suggest decreased recharge under future warming, although some high-latitude areas may see increased recharge as permafrost thaws (Taylor et al., 2013; Döll et al., 2012).

- Increased demand: Higher temperatures increase evapotranspiration and irrigation demand, intensifying groundwater extraction exactly when surface water availability may be declining (Famiglietti, 2014).

- Sea level rise: Threatens coastal aquifers through saltwater intrusion and inundation of recharge zones, compounding existing overextraction pressures (Werner et al., 2013).

- Contaminant mobilisation: Extreme rainfall events increase the risk of flushing surface contaminants into shallow aquifers, while droughts can concentrate solutes and exacerbate geogenic contamination (Taylor et al., 2013).

4.5 Land Use Change and Urbanisation

Land cover change profoundly affects groundwater recharge and quality (Scanlon et al., 2007). Deforestation alters the interception and transpiration of rainfall, often initially increasing recharge but destabilising soils and elevating erosion. Conversion of native vegetation to irrigated agriculture typically changes soil structure, increases solute leaching, and introduces new contaminant loads (Scanlon et al., 2007). Rapid urbanisation replaces permeable surfaces with impervious cover, reducing infiltration and recharge while simultaneously increasing runoff and surface water contamination (Foster & Chilton, 2003). Urban groundwater is additionally subject to the 'heat island' effect, with elevated temperatures altering microbial processes and contaminant fate (UNESCO-IHP, 2022).

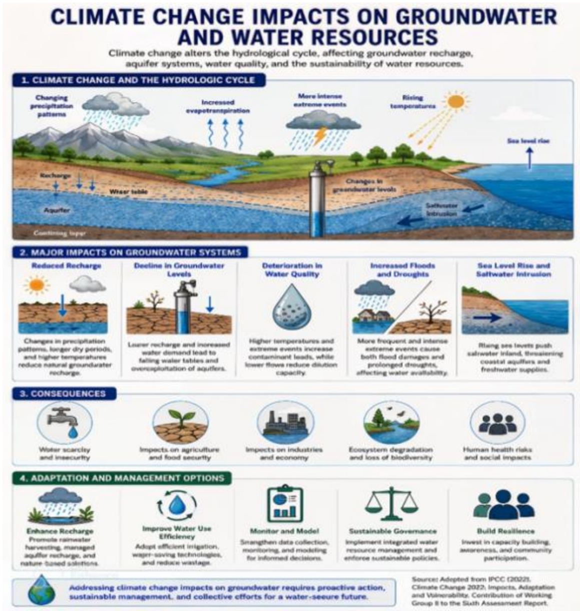

Fig 5: Climate Change Impacts

5. Saltwater Intrusion in Coastal Aquifers

Coastal aquifers are among the most intensively used and vulnerable groundwater systems in the world (Werner et al., 2013). The Ghyben–Herzberg relationship describes the natural equilibrium between fresh and saline groundwater in coastal settings, where a lens of freshwater floats above saltwater in proportion to the density difference. This equilibrium is inherently fragile. Excessive pumping reduces the hydraulic head of freshwater, allowing the saltwater wedge to advance inland and upward — a process termed saltwater intrusion (Werner et al., 2013).

Saltwater intrusion renders wells unusable for drinking and irrigation when chloride concentrations exceed critical thresholds (WHO guideline: 250 mg/L). It affects densely populated deltaic regions, small island developing states (SIDS), and low-lying coastal cities worldwide (Werner et al., 2013; Konikow, 2011). The phenomenon is being accelerated by rising sea levels, storm surges, and overextraction, creating a compound risk for coastal communities. Once contaminated by saltwater, aquifer recovery is extremely slow due to low permeability of fine sediments and slow flushing rates even after extraction is reduced (Custodio, 2002).

6. Groundwater Quality and Public Health

Groundwater quality is fundamental to public health, particularly in communities without access to treated piped water. Globally, an estimated 2 billion people rely on groundwater as their primary drinking source, often without adequate treatment or quality monitoring (UNESCO-IHP, 2022). The health burden from groundwater-borne illness and chemical exposure is enormous:

- Microbial contamination: Faecal pathogens from untreated sanitation cause diarrhoeal diseases — still a leading cause of child mortality in low-income countries. Shallow, unconfined aquifers in densely populated rural areas are most at risk (Foster & Chilton, 2003).
- Arsenic poisoning: Chronic arsenic exposure through drinking water causes arsenicosis, keratosis, skin lesions, and significantly elevated risks of cancers of the skin, bladder, and lung (Rahman et al., 2009).
- Nitrate: Infant methaemoglobinaemia ('blue baby syndrome') results from nitrate reduction in the immature infant gut. Adults face increased risk of colorectal cancer from chronic nitrate exposure (Foster & Chilton, 2003).
- Fluorosis: Long-term exposure to elevated fluoride causes dental mottling and, at higher concentrations, skeletal deformation, affecting hundreds of millions in endemic regions (Pandith Madhnure et al., 2015).

Effective surveillance, routine monitoring, and risk-based water quality management are essential to protect populations dependent on groundwater (UNESCO-IHP, 2022). However, monitoring infrastructure remains severely inadequate in many low- and middle-income countries, where the populations most dependent on groundwater are also the most exposed to quality risks (Gleeson et al., 2020).

7. Monitoring and Assessment Technologies

Effective management of groundwater requires robust monitoring and assessment. Advances in technology are transforming the field (Gleeson et al., 2020).

1. Remote sensing and satellite geodesy: The GRACE and GRACE-FO satellite missions measure gravitational anomalies to track large-scale changes in terrestrial water storage, including groundwater (Famiglietti, 2014; Döll et al., 2012). InSAR (Interferometric Synthetic Aperture Radar) detects land subsidence associated with aquifer compaction at millimetre precision (Konikow, 2011).

2. Hydrogeophysics: Electrical resistivity tomography (ERT), electromagnetic induction, and seismic methods enable non-invasive characterisation of aquifer geometry, lithology, and water quality. Nuclear magnetic resonance (NMR) directly measures water content and hydraulic properties (Foster & Chilton, 2003).

3. Environmental tracers: Isotopic tracers (tritium, ^{14}C, $^{3}H/^{3}He$, noble gases) provide quantitative constraints on groundwater age, recharge rates, and flow paths (Alley et al., 2002). Geochemical multi-tracer approaches illuminate mixing, residence time distributions, and recharge source attribution.

4. Numerical modelling: MODFLOW, FEFLOW, and other distributed parameter models simulate groundwater flow and solute transport, enabling scenario analysis for management planning (Gorelick & Zheng, 2015). Coupling with climate models allows projection of future system states under different emissions pathways (Taylor et al., 2013).

8. Management Strategies and Policy Frameworks

8.1 Integrated Water Resources Management (IWRM)

IWRM — the coordinated development and management of water, land, and related resources — provides a widely adopted framework for addressing groundwater challenges in the context of broader water system governance (UNESCO-IHP, 2022). Its key principles include basin-scale planning, stakeholder participation, and the integration of economic efficiency, social equity, and environmental sustainability (Gleeson et al., 2020). IWRM recognises that groundwater cannot be managed in isolation from surface water, land use, and societal water demands (Shah, 2009).

8.2 Managed Aquifer Recharge (MAR)

MAR encompasses deliberate techniques to enhance aquifer replenishment, including infiltration basins, recharge wells, wadi dams, and soil aquifer treatment (Gleeson et al., 2020). MAR has been successfully deployed in Australia, India, the USA, Israel, and several European countries to buffer seasonal variability, restore depleted aquifers, and treat water through passage through the subsurface (UNESCO-IHP, 2022). Ensuring source water quality and preventing clogging of recharge infrastructure are key operational challenges.

8.3 Groundwater Governance and Regulation

Effective governance is essential to translate scientific understanding into sustainable management (Shah, 2009). Groundwater governance encompasses legal frameworks defining water rights and use entitlements, regulatory oversight of extraction and pollution, economic instruments (groundwater pricing, abstraction fees), community-based management, and transboundary agreements for shared aquifer systems (Gleeson et al., 2020). Many countries face a significant 'governance gap' — with groundwater de facto unregulated despite nominal legal provisions — driven by the difficulty of monitoring distributed extraction and the political sensitivity of restricting agricultural water use (Shah, 2009; Gorelick & Zheng, 2015).

8.4 Remediation Technologies

Where contamination has occurred, remediation options range from active engineered interventions to passive natural attenuation (Foster & Chilton, 2003). Pump-and-treat systems — the historical default — are effective for plume containment but may require decades of operation for aquifer restoration. In situ technologies, including permeable reactive barriers, bioremediation, and chemical oxidation/reduction, offer more targeted approaches (Gleeson et al., 2020). Natural attenuation — relying on biodegradation, dilution, dispersion, and sorption — may be appropriate where risk is acceptable and monitoring demonstrates declining concentrations. For geogenic contaminants, treatment at the point of use (household filters, community treatment plants) is often more practical than aquifer-scale intervention (Rahman et al., 2009; Pandith Madhnure et al., 2015).

9. Case Studies

9.1 The Ogallala Aquifer, USA

The High Plains (Ogallala) Aquifer underpins irrigated agriculture across eight US states, supplying water for approximately 30% of US groundwater irrigation (Sophocleous, 2010). Accumulated over millennia under wetter Pleistocene climates, recharge rates are negligible relative to current extraction. Groundwater levels have declined by more than 30 metres in heavily irrigated portions of Kansas and Texas (Wada et al., 2010). Without dramatic changes in water use efficiency or crop patterns, depletion of the southern portions of the aquifer within decades poses an existential threat to High Plains agriculture, with significant national food security implications (Sophocleous, 2010; Famiglietti, 2014).

9.2 Arsenic in the Bengal Basin, South Asia

The discovery of widespread arsenic contamination in shallow tubewells across Bangladesh and West Bengal in the 1990s — initially installed to avoid surface water-borne diseases — revealed a geogenic hazard of unprecedented scale (Bhattacharya et al., 2007). An estimated 35–77 million people were potentially exposed above WHO thresholds (Rahman et al., 2009). The contamination results from reductive dissolution of arsenic-bearing iron oxyhydroxide minerals in the young Holocene alluvial sediments under anaerobic conditions. Responses have included alternative water sources (deep aquifers, surface water treatment), arsenic removal technologies, and mitigation through community education, though ensuring sustainable, safe water access for all affected communities remains an ongoing challenge (Bhattacharya et al., 2007).

9.3 Mexico City: Subsidence and Groundwater Stress

Mexico City provides one of the most dramatic examples of urban groundwater overexploitation. The city, built on the lacustrine clays of the former Lake Texcoco, has experienced land subsidence of up to 10 metres over the past century due to aquifer compaction (Konikow, 2011). Subsidence continues at rates exceeding 30 cm per year in some areas, causing widespread infrastructure damage, flooding, and the paradoxical situation of a water-stressed city sinking while facing acute supply shortages (Custodio, 2002). The case illustrates how groundwater governance failures in rapidly growing cities can create compounding, difficult-to-reverse environmental and engineering disasters (Shah, 2009).

10. Discussion and Future Directions

The synthesis presented in this review reveals a global groundwater system under profound and accelerating stress (Gleeson et al., 2020; Gorelick & Zheng, 2015). The challenges of overexploitation, contamination, climate change, and inadequate governance are interconnected and often self-reinforcing (Famiglietti, 2014). Aquifer depletion increases vulnerability to drought; contamination reduces the effective supply of usable water; climate change alters recharge patterns and increases demand; and governance failures allow unsustainable practices to continue despite scientific warnings (Taylor et al., 2013; Shah, 2009).

Several priority areas emerge for future research and action. First, improved global groundwater monitoring — particularly in data-sparse regions of Sub-Saharan Africa, South and Southeast Asia, and Latin America — is essential (UNESCO-IHP, 2022). The deployment of low-cost sensor networks, citizen science, and remote sensing fusion offers promising pathways (Gleeson et al., 2020). Second, process understanding of recharge under non-stationary climate conditions requires continued investment (Taylor et al., 2013; Döll et al., 2012). Third, integrated socio-hydrological research that couples hydrogeological understanding with economic behaviour, institutional analysis, and equity considerations is needed to design governance interventions that are effective in practice, not only in theory (Shah, 2009; Gorelick & Zheng, 2015).

The emerging 'Safe and Just Groundwater Space' concept — analogous to planetary boundaries — provides a useful framing for defining ecologically safe and socially equitable bounds for groundwater use (Gleeson et al., 2020). Translating this concept into operational management targets requires further development of groundwater accounting frameworks at aquifer, national, and global scales (Gleeson et al., 2012). International cooperation on transboundary aquifers — currently governed by a patchwork of bilateral and multilateral agreements — deserves strengthening through capacity building and multilateral frameworks (UNESCO-IHP, 2022).

11.Conclusion

Groundwater is essential for freshwater supply, agriculture, ecosystems, and human health worldwide. However, it faces increasing threats from overexploitation, contamination, climate change, and land-use changes, leading to depletion, land subsidence, and serious public health risks, especially for vulnerable populations. Addressing these issues requires integrated and interdisciplinary management approaches involving hydrogeology, environmental science, governance, and public health. Although strategies such as integrated water resources management, managed aquifer recharge, and advanced monitoring systems are available, their implementation remains inadequate. Sustainable groundwater management ultimately depends on recognizing groundwater as a finite and ecologically connected resource, supported by stronger policies, institutional reforms, scientific advancement, and long-term investment in monitoring and protection systems.

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Impact of Rainfall Variability on Groundwater Recharge in Semi-Arid Regions

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Introduction

Rainfall is one of the most important natural resources, supporting life, agriculture and ecosystems. In semi-arid regions, rainfall plays a crucial role in maintaining groundwater resources, which serve as the primary source of water for irrigation, domestic use, and livestock. Unlike perennial rivers, many semi-arid areas depend heavily on seasonal monsoon rainfall to replenish groundwater reserves via infiltration and recharge. Therefore, even small variations in rainfall patterns can significantly affect water availability and agricultural productivity in the region.

Groundwater has become essential for rural communities, especially where surface water is scarce or unreliable. Farmers are increasingly relying on bore wells for irrigation because of unpredictable rainfall and drought. However, over-extraction and insufficient recharge have caused groundwater levels to decrease in many regions of India. The rising water demand from agriculture, urban growth, and population increase has further strained groundwater resources.

In recent decades, water scarcity has become a significant environmental and socio-economic issue. Irregular rainfall, delayed monsoons, extended droughts, and rising temperatures have diminished natural groundwater recharge. Changes in climate variability and climate change are shifting traditional rainfall patterns, causing extreme weather events, such as heavy rainfall over brief periods, followed by prolonged dry spells. These conditions frequently lead to increased surface runoff and decreased soil infiltration, restricting groundwater replenishment. Therefore, understanding the relationship between rainfall variability and groundwater recharge is essential for sustainable water resource management.In semi-arid ecosystems, effective rainwaterharvesting, watershed management and groundwater recharge practices are becoming increasingly important for ensuring long-term water security and agricultural sustainability.

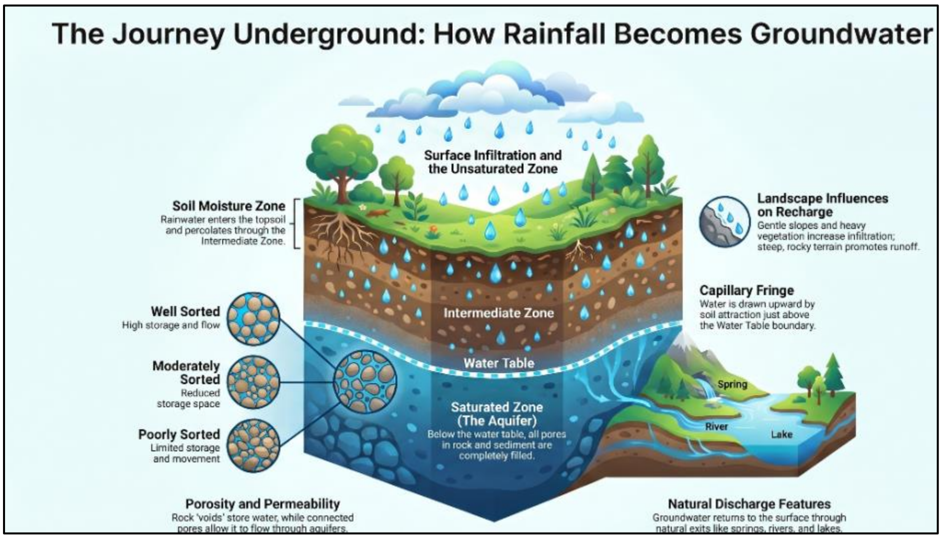

Fig.1: Relationship between rainfall and groundwater

Groundwater recharge is closely linked to rainfall, as rainwater is the primary source for replenishing underground aquifers in semi-arid regions. When it rains, some water flows as surface runoff, while another portion infiltrates the soil. The infiltrated water gradually moves downward through soil pores and rock layers until it reaches the groundwater. This natural process is known as groundwater recharge. The amount of recharge mainly depends on rainfall intensity, duration, soil characteristics, vegetation cover, and land slope.

Infiltration plays a critical role in determining how much rainwater enters the subsurface. Gentle, continuous rainfall generally promotes better infiltration because the soil can gradually absorb water. In contrast, intense rainfall over a short period often generates higher runoff, thereby reducing the amount of water available for recharge. Therefore, not all rainfall contributes equally to the replenishment of groundwater.

The Central Ground Water Board (CGWB) reports thatthe effectiveness of groundwater recharge in semi-arid regions depends largely on rainfall intensity, soil type, land slope and vegetation cover. In areas dominated by clay soils, infiltration is generally slow due to low permeability, resulting in higher surface runoff and limited recharge. Sandy clay soils, however, allow moderate infiltration and comparatively better groundwater replenishment. Sparse vegetation and sloping lands further reduce infiltration by accelerating runoff during intense rainfall events.

Climate variability has intensified groundwater stress in semi-arid ecosystems. Irregular monsoon patterns, delayed rainfall onset and extreme rainfall events reduce the efficiency of natural recharge processes. Although short-duration heavy rainfall may increase total rainfall amounts, much of the water is lost as runoff instead of infiltrating into the ground. At the same time, increasing dependence on bore wells for irrigation has led to excessive groundwater extraction and declining water tables in many semi-arid regions of India.

To address these challenges, the CGWB emphasizes the importance of rainwater harvesting, watershed management, artificial recharge structures, GIS-based groundwater mapping and modern monitoring technologies. Sustainable groundwater management practices are essential for improving recharge, reducing water scarcity and ensuring long-term agricultural and environmental sustainability in semi-arid regions.

Groundwater Recharge in Semi-Arid Areas

Groundwater recharge is essential for sustaining water availability in semi-arid regions where rainfall is seasonal and highly variable. Several practical water conservation methods help improve infiltration, reduce runoff and enhance groundwater storage.

***Farm Ponds**:* Farm ponds store rainwater during monsoon periods and allow gradual infiltration into the soil, supporting groundwater recharge and supplemental irrigation during dry spells.
***Check Dams**:* Small barriers constructed across streams slow down runoff, increase water retention time, and promote percolation into underground aquifers.
***Percolation Tanks**:* These are shallow reservoirs designed to collect surface runoff and enhance seepage into the ground, particularly in hard-rock and semi-arid regions.
***Rainwater Harvesting**:* Collection and storage of rooftop and surface runoff water help reduce water wastage and improve groundwater recharge in rural and urban areas.
***Watershed Management**:* Integrated watershed practices such as contour bunding, afforestation, trenching and soil conservation practices reduce erosion, improve infiltration, and increase groundwater recharge efficiency.

Advanced Technologies to Study Rainfall - Groundwater Relationship

Advanced technologies have aided in accurately understanding how rainfall influences groundwater recharge and water table fluctuations. Modern tools provide real-time monitoring, spatial analysis and predictive modeling for sustainable groundwater management (SGM).

Automatic Weather Stations (AWS):They are used to collect real-time rainfall, temperature and humidity data to analyze rainfall variability and recharge patterns.
***Groundwater Monitoring Sensors**:*Digital water-level recorders and piezometers continuously measure groundwater fluctuations after rainfall events.

Remote Sensing*:* Satellite data help monitor rainfall distribution, soil moisture, vegetation cover and groundwater storage over large regions.

Geographic Information System (GIS):GIS integrates rainfall, soil, slope and land-use data to identify groundwater recharge zones and potential areas.

Digital Twin Technology*: It* creates virtual models of watersheds using real-time rainfall and groundwater data to simulate the recharge processes and predict future water availability.

Artificial Intelligence (AI) and Machine Learning (ML):AI models, such as Artificial Neural Networks (ANN), Random Forest (RF) and Long Short-Term Memory (LSTM) models have been used to forecast groundwater levels and analyze complex rainfall–groundwater relationships.

IoT-Based Sensors:Internet of Things (IoT) devices provide continuous monitoring of rainfall, soil moisture and groundwater conditions for smart water management purposes.

Climate Change and Future Water Security

Climate change is significantly affecting water resources in semi-arid regions through changing rainfall patterns and increasing climate variability. Uncertain monsoon onset, irregular rainfall distribution, and reduced rainy days are making agriculture and groundwater recharge more difficult to predict.

Extreme rainfall events are becoming more frequent, where large amounts of rain occur within short durations. Such intense rainfall often increases surface runoff and flooding instead of allowing sufficient infiltration for groundwater recharge. At the same time, longer dry spells between rainfall events increase soil moisture stress, reduce crop productivity and intensify dependence on groundwater extraction.

Continuous over-exploitation of groundwater combined with declining natural recharge poses a serious threat to future water security. Therefore, sustainable groundwater management has become essential in semi-arid regions. Practices such as rainwater harvesting, artificial recharge structures, efficient irrigation methods, watershed management, and scientific groundwater monitoring can help improve groundwater sustainability and climate resilience.

Fig. 2: Groundwater: Invisible water reserves for sustainable agriculture.

Conclusion

Groundwater is essential in semi-arid areas, providing water for agriculture, drinking, and local rural needs. Nonetheless, climate variability, unpredictable monsoon patterns, heavy rains, and over-extraction threaten this vital resource. Thus, understanding rainfall patterns and their influence on groundwater recharge is essential for sustainable management. Integrating scientific rainfall analysis with conservation techniques such as farm ponds, check dams, percolation tanks, rainwater harvesting and watershed management practices can significantly improve groundwater sustainability. Groundwater is now essential for ensuring water security, boosting agricultural productivity, and preserving environmental health for future generations in semi-arid regions.

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Too Small to See, Too Big to Ignore!

How Microplastics Have invaded Indian Cities

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Introduction

Every morning, millions of Indians step into streets where plastic waste is visible. The more serious threat, however, is often invisible. Larger plastic items slowly break down into particles smaller than 5 mm, known as microplastics. These particles are now reported in rivers, lakes, air, soil, sediments, food products and even human tissues. The problem, therefore, is not only one of municipal cleanliness, but also of environmental exposure, public health and urban governance.

The term microplastics entered scientific use after Richard Thompson and colleagues documented tiny plastic fragments in marine environments in 2004 (Thompson et al., 2004). Later, Geyer et al. (2017) showed the scale of the global plastic problem: of all plastic produced up to 2015, only about 9% had been recycled, 12% incinerated and nearly 79% had accumulated in landfills or the natural environment. These findings changed the discussion from visible plastic waste to long-term contamination by persistent particles.

What Are Microplastics and Where Do They Come From?

Microplastics are generally classified into primary and secondary forms. Primary microplastics are manufactured at small sizes, such as microbeads, industrial pellets and synthetic fibres released from polyester or nylon textiles during washing. Secondary microplastics are formed when plastic bottles, bags, packaging, tyres, pipes, insulation materials and other objects fragment under sunlight, heat, friction and mechanical abrasion.

Indian cities are major sources because they combine high plastic consumption, dense roads, construction activity, open waste burning, inadequate segregation and stormwater drains that transfer street debris directly into rivers and lakes. Tyre wear, textile fibres, construction dust, fragmented packaging and unmanaged solid waste are major urban sources. Monsoon runoff further mobilises these particles, carrying them into drains, surface water bodies, soil profiles and potentially shallow groundwater systems.

How Microplastics Are Detected: Global Methodology

Worldwide detection follows a broad sequence: sampling, extraction, purification, visual sorting, polymer identification and quantification. Sampling methods depend on the medium. Water samples are collected using plankton nets, manta trawls, sieves and filtration units. Soil and sediment samples are collected through corers, grab samplers or stainless-steel scoops. Airborne microplastics are collected through passive deposition samplers, high-volume air samplers and filter-based monitoring devices. Strict contamination control is essential because fibres from synthetic clothing and laboratory air can easily distort results.

After collection, samples are filtered and separated into size classes such as 1-5 mm, 300 micrometre to 1 mm and below 300 micrometres. Density separation is commonly used for soil and sediment: the sample is mixed with sodium chloride, zinc chloride or sodium iodide solution so that lighter plastic particles float while heavier mineral grains settle. Organic matter is then removed using hydrogen peroxide, potassium hydroxide, enzymatic digestion or Fenton reagent, depending on sample type.

Preliminary identification is done under a stereomicroscope or optical microscope by recording particle shape, colour and form - fibre, fragment, film, foam, bead or pellet. Nile Red staining is also used as a rapid screening method because many plastic particles fluoresce under specific light conditions. However, visual methods alone are not enough. Confirmatory polymer identification is generally done using Fourier

Transform Infrared Spectroscopy (FTIR), Raman spectroscopy or Pyrolysis-Gas Chromatography/Mass Spectrometry (Py-GC/MS). FTIR and Raman identify the polymer type at the particle level, while Py-GC/MS estimates polymer mass through thermal breakdown products. Results are reported as particles per litre for water, particles per kilogram for soil or sediment, particles per square metre per day for atmospheric deposition, and particles per tissue or food sample for biological studies.

Indian Cities: State of Knowledge

Indian research has expanded rapidly. Sruthy and Ramasamy (2017) reported microplastics in sediments of Vembanad Lake, Kerala, demonstrating contamination even in a Ramsar-designated freshwater ecosystem. Subsequent reviews by Veerasingam et al. and Vaid et al. showed that microplastics occur across marine sediments, freshwater bodies, groundwater, fish gut contents and food-grade table salts. A major limitation repeatedly highlighted is the absence of standardised methods, which makes comparison between cities and regions difficult.

Recent city-level studies make the issue more actionable. In Malda, West Bengal, airborne microplastic deposition was reported at 122-387 particles per square metre per day, mainly linked to commercial activity (Mandal et al., 2024). In Indore, ICMR researchers detected microplastics in agricultural and recreational soils, showing that urban cleanliness rankings do not necessarily reflect plastic particle contamination (Singh et al., 2024). Studies from South India have mapped abundance across residential, commercial and green spaces (Mohan et al., 2025), while work from Kerala shows how monsoon runoff and weak waste systems intensify aquatic contamination (Shini et al., 2025). Evidence from urban compost also suggests that material used to improve farmland may itself become a pathway for microplastic transfer (Mohanty et al. 2026).

Health and Governance Concerns

Microplastics are increasingly reported in human lungs, liver, blood, placenta and other tissues. They may cause inflammation, cellular stress and chemical exposure because plastic particles can carry additives, pesticides and heavy metals. Urban residents face exposure through air, food and drinking water. A 2024 study in the New England Journal of Medicine reported that patients with microplastics detected in arterial plaque had a higher risk of heart attack, stroke or death during follow-up (Marfella et al. 2024). The study does not prove direct causation, but it strongly reinforces the need to treat microplastics as a public-health concern rather than only a waste-management problem.

What Needs to Happen

India needs a coordinated response. Airborne microplastics should be included in systematic urban air monitoring. Source reduction must be prioritised through strict enforcement of single-use plastic controls and Extended Producer Responsibility. Open burning of waste must be eliminated by expanding door-to-door collection, segregation and processing services, especially in low-income and high-density areas. Stormwater drains should be redesigned to retain pollution rather than transfer it directly to rivers through the use of wetlands, bioswales, retention ponds and silt traps.

A national research programme is also required to standardise sampling, laboratory protocols, reporting units and quality-control procedures. Drinking water, groundwater sources, open wells and bore wells in urban areas should be brought under microplastic surveillance. The science is now clear enough for policy action. Microplastics are not a future risk; they are already embedded in the air, water, soil and metabolism of Indian cities.

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