



Vol. 05, Issue - December 2025

e - Journal of Geohydrology



**Indian National Chapter
of
International Association of Hydrogeologists**

Online Journal of INC-IAH

Message from the President
International Association of Hydrogeologists – India Chapter (INC-IAH)
On the Occasion of the Release of the 5th volume of December 2025 issue of
e-Journal of Geohydrology

Prof. (Dr) A. K. Sinha

Vice-President Asia (IAH Council) &
President, Indian Chapter of IAH



Dear Colleagues,

It gives me immense pleasure to share my view with the members of the International Association of Hydrogeologists on the momentous occasion of releasing the **5th volume of the e-Journal of Geohydrology**. This continued progress is a testament to our collective commitment to advancing groundwater science, fostering research culture, and strengthening professional exchange in the hydrogeological community. Since its inception, the e-Journal has served as a dedicated platform for researchers, practitioners, and young professionals to share innovative ideas, scientific findings, and practical solutions to the pressing groundwater challenges facing our nation and the world. The growing interest in the journal reflects the vibrancy and depth of our groundwater community and reinforces the relevance of our shared mission. Today, as water security becomes an increasingly critical concern—whether in terms of declining groundwater levels, deteriorating quality, or rising stress across rural and urban sectors—the need for science-based, field-tested, and forward-looking solutions has never been greater. I am confident that this issue of the journal will once again inspire meaningful dialogue and stimulate further research on sustainable groundwater management, aquifer restoration, climate resilience, and innovative hydrogeological practices.

I take this opportunity to express my heartfelt appreciation to **Prof. B. S. Chaudhary, Executive Editor**, and to the distinguished Editorial Team particularly **Ms. Suhani Srujanika**, a young dedicated researcher for their dedication, meticulous effort, and unwavering commitment to enhancing the quality and visibility of this publication. I also extend my sincere gratitude to all contributing authors for their valuable manuscripts and for placing their trust in INC-IAH. The Governing Body remains committed to strengthening the journal further—through wider outreach, academic collaborations, and by securing formal registration and ISSN/ISBN recognition in the near future. We also envision expanding scientific activities such as lecture series, training programs, workshops, and collaborative research initiatives to nurture the next generation of hydrogeologists.

On behalf of the entire Governing Body of INC-IAH, I congratulate everyone associated with the successful release of this 5th issue. I invite all members, students, and professionals to engage with the journal, share their insights, and continue contributing to this growing knowledge platform.

I wish you all an enriching and enjoyable reading experience.

With warm regards,

Prof. (Dr.) A. K. Sinha

President, INC-IAH

Message from the INC-IAH Editorial Board

On the Release of the 5th Volume December 2025 issue of the
E-Journal of Geohydrology

It gives us immense pleasure to present the 5th Volume of the *E-Journal of Hydrogeology*, a milestone that reflects our collective commitment to advancing knowledge, fostering dialogue, and strengthening professional collaboration in the field of groundwater science. Over the past years, this e-journal has evolved into a platform that brings together researchers, practitioners, policy experts, and young scholars who share a common dedication to understanding and sustainably managing one of the world's most vital resources—groundwater.

The present issue continues our tradition of highlighting emerging trends, innovative methodologies, and field-based insights that address the complex challenges facing hydrogeological systems in India and globally. From aquifer characterization and groundwater quality assessment to climate-resilient groundwater management and transboundary water cooperation, the contributions in this volume reflect both scientific rigor and societal relevance. Each article underscores the importance of evidence-based decision-making for water security in an era of increasing environmental stress.

The Editorial Board extends its heartfelt appreciation to all authors for their high-quality submissions, to the reviewers for their meticulous evaluations, and to our readers for their continuous encouragement and engagement. We also gratefully acknowledge the support of the International Association of Hydrogeologists (IAH) and the active involvement of the Indian National Chapter, whose vision has been instrumental in nurturing this journal.

As we look forward, we remain committed to expanding the journal's reach, strengthening its academic impact, and creating a nurturing environment for early-career researchers. We encourage our scientific community to continue contributing original research, case studies, and perspectives that enrich the discourse around groundwater sustainability.

On behalf of the entire Editorial Board, we are delighted to release this 5th Volume, December 2025 issue, and we hope it inspires further inquiry, collaboration, and innovation for the better management of groundwater resources. We thank you for being a part of this continued journey and look forward to your valuable participation in the coming volumes.

INC-IAH Editorial Board:

Prof. Bhagwan Singh Choudhary

Prof Bhavana Umrikar

Dr Gopal Krishan

Ms Suhani Srujanika

Dr Vijay Pal Meena

Dr Jabbar Khan



EDITORIAL BOARD

Executive Editor:

*Prof. (Dr.) B.S. Chaudhary
Department of Geophysics,
Kurukshetra University, Haryana
Email: bschaudhary@kuk.ac.in*

**Associate Executive
Editors:**

*Prof. (Dr.) Bhavana Umrikar
Department of Geology
Savitribai Phule Pune University, Pune*

*Dr. Gopal Krishan
National Institute of Hydrology,
Roorkee, Uttarakhand*

Editors:

*Suhani Srujanika
Research Scholar
Savitribai Phule Pune University, Pune*

*Dr. Vijay Pal Meena,
Asst. Professor,
Department of Geology,
University of Rajasthan, Jaipur*

*Dr. Jabbar Khan,
Asst. Professor,
Centre for Environmental Studies,
JERC University, Jaipur*

Declaration: the views/opinions expressed by authors of the papers included in this issue of Journal are their own and may not necessarily reflect the views of the Editorial Board of the Journal. They are solely responsible for copy right/ legal issues, if any.



Governing Body INC of IAH (2024-25)

President	Prof. (Dr.) A.K. Sinha
Vice-President	Dr. Anadi Gayen
Secretary	Prof. (Dr.) Bhagwan Singh Choudhary
Treasurer	Dr. Ashok Kumar
Executive Members	Prof. (Dr.) Bhavana Umrikar Sh. Sujit Sinha Prof. (Dr.) R. P. Singh Ms. Chirashri Mohanty Dr. Ashwani Kumar Tiwari

CONTENTS

Sr. No.	Title of the paper	Authors	Page No.
1.	Evolution of Groundwater Quality –An Overview	G. Krishna Rao and Ranveer Nandan	1 – 10
2.	A Critical Review of Groundwater Assessment, Estimation, and Regulatory (AER) Integration in India: Towards a Linked Framework	Nitish Kumar, Md Noor Uddin, Amit Kumar, Rambabu Singh	11 – 18
3.	Impact Assessment Study on Groundwater levels in part of the States of North East India	S Somarendro Singh	19 – 29
4.	Delineation of Groundwater Recharge Potential Zones using Geospatial Techniques: A Comparative Analysis of Raster Calculator and Weighted AHP Tools	Suhani Srujanika, Prabhu Prasad Das, Bhavana Umrikar	30 – 41
5.	Assessing Drought Vulnerability in parts of Nira River Basin, Western India, using GIS and AHP Methods	Payal V. Waindeshkar, Bhavana Umrikar, Saikat Sengupta	42 – 49
6.	Evaluation of Basaltic Aquifers from Western India for Efficient Resource Management	Himanshu Gaikwad, Chitra Desai, Bhavana Umrikar	50 – 68
7.	Delineation of Groundwater Potential Zones using Remote Sensing and GIS: A Case Study from Ghatkesar, Telangana	Shaik Saleemmiya	69 – 79
8.	Managing Groundwater for Sustainable Livelihoods: Insights from Chambal Ravines, Keshorai Patan Block, Bundi District, Rajasthan	Sayelli Tembhurne	80 – 90
9.	Ground Water Studies of Upper Indravati Irrigation Project, Odisha	S. K. Sharma and Lalit Gupta	91 – 105
10.	Assess & Evaluate Impact of Bore-Charger Activity on nearby Water Bodies: A Case Study of Khalad, Purandar, Maharashtra India	Vinit Phadnis	106 – 123
11.	Understanding the Hydrodynamics of parts of Araria District, Bihar using Geospatial Technique	Anugya Rashi, Anil Kumar, Bhavuk Sharma	124 – 129
12.	Landslide Susceptibility Mapping in Western Ghats using AHP-Weighted Overlay Modelling: A Case Study of Patan Taluka, Satara, India	Amit Vijaykumar Shirke, Bhavana Umrikar	130 – 140
13.	Groundwater monitoring- Data Management, Assessment and its Uncertainties Statistical Assessment of Underground Water Quality at Moradabad (Uttar Pradesh, India)	G. K. Rastogi, N. Kumar and D. K. Sinha	141 – 145
14.	Delineating Groundwater Potential Zones in Dibrugarh District, Assam, India using GIS and Analytical Hierarchy Process (AHP)	Bijoy K. Chetia, Jayashri Dutta, William Narzary	146 – 157
15.	Hydrogeomorphological Studies for Groundwater Prospecting using IRS -1D, LISS III Image in parts of Agra District, UP, India	Liaqat A.K.Rao and Ruby Siddiqui	158 - 162



Evolution of Groundwater Quality –An Overview

G.Krishna Rao¹, Ranveer Nandan²

1. Retd. Professor of Geology, Andhra University

2. Head, Department of Geology, B.N.College, Patna

E-mail: geokrsna@gmail.com

Abstract

Meteoric water (H_2O) that enters in to the mineral structures of a rock splits into H^+ and OH^- components which react with the elements in the lattice structures of the minerals. Na^+ , K^+ , Ca^{2+} , and Mg^{2+} combine with OH^- to form their hydroxides which are soluble. The H^+ joins silicon tetrahedra to form silicic acid (H_4SiO_4) which is also soluble. Fe is released from ferric minerals to form iron hydroxide which precipitates. However, these major constituents exist in the form of cations and anions. Anions are predominantly HCO_3^- and Cl^- . Organic matter in the soil zone oxidizes into organic carbon. Reducing environment is created locally. Quartz mineral is subjected to dissolution under low pH. This primary reaction of rocks takes place mainly in the zone of aeration. In the zone of saturation, some modification in the quantum of chemical constituents takes place through adsorption, absorption and replacement of these ions in to or from the aquifer materials. SO_4^{2-} and NO_3^- are mainly added due to pollution from domestic and industrial sources. Cl^- is derived mainly from rainfall as an outfall of sea water. CO_3^{2-} is mainly related to carbonate rock sources.

Geo-environmental factors like rainfall, soils, rock types, topography, permeability of aquifer materials, contamination or pollution aspects modify the quality of ground waters from place to place in a region and in different areas. These aspects are discussed with case studies from Tamil Nadu and Andhra state.

Keywords: Evolution, Groundwater quality, Mineral structure, Meteoric water, Environmental metrics

Introduction

Groundwater constitutes the largest accessible source of freshwater on Earth and plays a critical role in sustaining domestic, agricultural and industrial demands, particularly in semi-arid and monsoonal regions such as India. The chemistry of groundwater reflects the interaction between water and geological materials, the residence time within the aquifer, and superimposed anthropogenic influences such as agriculture, industry, and urbanization (Freeze & Cherry, 1979; Appelo & Postma, 2005).

Traditionally, hydrogeochemical studies have focused on measuring the concentration of dissolved ions in groundwater and relating them to aquifer characteristics. In contrast, the present study initiates the discussion from the primary release of chemical constituents during rock weathering, which forms the foundation of groundwater chemistry. This approach follows earlier work by Krishna Rao (1984), who demonstrated that the hydrogeochemical signatures in groundwater are strongly linked to the mineralogical transformations taking place during chemical weathering.

Water acts as a highly reactive bipolar molecule capable of dissociating into H^+ and OH^- ions, driving silicate hydrolysis, cation exchange, dissolution–precipitation reactions, and secondary mineral formation. These processes govern the release of major ions (Ca^{2+} , Mg^{2+} , Na^+ , K^+), bicarbonate generation, mobility of trace elements, and evolution of groundwater quality in different geological

settings (Hem, 1985; Clark, Fritz 1997; Edmunds & Smedley, 2001). Water is Enemy No.1 to rocks, it is said because it is bipolar with H^+ and OH^- molecular structure. Cations like K^+ , Na^+ , Ca^{2+} and Mg^{2+} are attracted to OH^- to become their hydroxides which are soluble and hence pass out through the infiltrating waters. H^+ on the other hand joins with the silicon tetrahedra in the lattice structure and become silicic acid (H_4SiO_4) which is also soluble and hence drained out. Ferric iron joins with OH^- and becomes ferric hydroxide which is insoluble and hence precipitates insitu. Ferrous iron oxidizes to become ferric iron and precipitates. Quartz is also found to be undergoing dissolution in the advanced stage of weathering under acidic environment. Aluminum also become as its hydroxide and precipitates. Thus, the weathered residue turns out to be bauxite, laterite or even clayey product depending on the local environment in the weathering front and internal drainage conditions.

Given the rapid changes in land use, intensive agriculture, urbanization, and climate-driven stress on aquifers, understanding these processes is essential for developing sustainable groundwater management strategies. This paper revisits the evolution of groundwater quality with case studies from crystalline, sedimentary, and unconsolidated aquifers, highlighting the influence of geo-environmental factors.

Chemistry of groundwater reveal these chemical constituents exist as ions -cations and anions only. Carbon is added during this weathering process from oxidation of organic matter in the soil zone. Therefore, bicarbonates (HCO_3^-) are present in predominance combining with hydrogen. Organic matter is decomposed creating humic acids in the soil zone. In the process of oxidation of organic matter, carbon is generated and reducing environment is created in the weathering front. Therefore, organic matter plays vital role in the mobility of bivalent elements like Fe and As (Arsenic) which become soluble under reducing conditions. Humic acids create acidic conditions which help their mobility.

Problems Arising from Groundwater Quality

Groundwater quality has emerged as a major environmental and public-health concern globally, with issues ranging from natural geogenic contamination to widespread anthropogenic pollution. In many regions, groundwater deterioration directly impacts drinking-water safety, irrigation suitability, soil health, and ecosystem functioning.

Global Perspective

Major global groundwater quality challenges include Fluoride contamination in East Africa, China, India leading to dental and skeletal fluorosis; Arsenic mobilisation in Bangladesh, Nepal, Vietnam, and India due to reductive dissolution of Fe-oxyhydroxides. Nitrate pollution from intensive agriculture in Europe, US and Asia; Salinity and seawater intrusion in coastal aquifers due to over-abstraction and sea-level rise; Industrial solvents, pesticides, pharmaceuticals increasingly detected worldwide.

India-Specific Groundwater Quality Problems

India faces diverse groundwater quality issues due to its varied geology, climate, agricultural intensity, and rapid urbanisation. Major issues include Fluoride as twenty Indian states report fluoride above the BIS permissible limit (>1.5 mg/L). Chronic exposure leads to fluorosis, affecting millions (CGWB, 2023). The Indo-Gangetic plains of West Bengal, Bihar, Uttar Pradesh, Assam and Jharkhand are severely affected by Arsenic. Arsenic >50 $\mu\text{g/L}$ is common due to reducing aquifer conditions, similar to the mechanism described in this paper. High iron ($>1-3$ mg/L) is common in eastern and north-eastern India (Assam, Tripura, Odisha, Jharkhand). It causes staining, pipe clogging and unpleasant taste. Nitrate levels in agricultural belts frequently exceed 45 mg/L (BIS limit), caused by fertilisers,

septic tanks, and organic waste. High levels cause methaemoglobinaemia in infants. Coastal Gujarat, Tamil Nadu, Andhra Pradesh and Odisha show significant salinity owing to seawater intrusion due to over-pumping, especially during summer. Heavy Metals & Industrial Pollutants such as Hexavalent chromium, lead, nickel and industrial solvents are reported in industrial clusters (Vellore, Kanpur, Ahmedabad, Hyderabad). Crystalline aquifers often produce hard water rich in Ca–Mg–HCO₃, requiring treatment for domestic use.

Chemistry of Weathering Process

Chemical analyses of fresh rocks and their completely weather products (rocks retaining their texture) in the Shevaroy hills are shown in table- 1 below (Krishna Rao, op.cit). In the three types of rocks, namely, mafic charnockite, Intermediate charnockite and garnetiferous felsic rocks, aluminum and ferric iron are enriched. It infers that they are insoluble in water. Ferrous iron as FeO shows decline as it is soluble under reducing environment. Calcium is mostly leached out. Magnesium also shows the same behavior except in garnetiferous gneisses. Garnets are relatively more resistant to weathering. Sodium and potassium are nearly leached out during weathering itself. These rocks ultimately changed to bauxite because of high rainfall and high-altitude facilitating removal of soluble elements with circulating waters. Bauxite and laterite are the end products depending on local geo-environmental conditions and secondary enrichment of either aluminum or iron on some of the hill peaks.

Table 1: Chemical Composition of crystalline Rocks and weathered Rocks, Shevaroy hills, Salem district,T.N, (in %)

S.No.	Rock Type	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	CaO	MgO	K ₂ O	Na ₂ O
1.	Mafic Charnockite	47.72	15.20	8.04	7.12	12.10	4.19	0.70	4.65
a	Completely weathered	3.70	46.82	28.72	3.60	0.74	0.21	Trace	trace
2	Mafelsic Charnockite	60.32	17.30	4.08	4.70	3.70	2.03	1.90	5.25
a	Completely weathered	35.59	36.20	7.65	1.07	0.89	0.17	Trace	trace
3	Garnetiferous felsic rock	70.10	13.02	2.17	5.20	2.62	0.54	1.70	3.50
a	completely weathered	42.56	19.26	23.23	1.20	0.40	0.50	0.20	0.25
Visakhapatnam Area (C.S,Murthy, in SubbaRao et al 1996)									
	Khondalite					0.83	1.34	1.69	0.41
	Leptynite					1.50	0.29	5.69	2.35
	Charnockite					2.81	0.75	5.18	2.06

Chemistry of Groundwaters in Crystalline Rocks

Crystalline rocks include mafic, mafelsic and felsic rocks represented by charnockites, granitic gneisses and garnetiferous gneisses such as leptynites and khondalites. Basic chemical composition of these rocks remain more or less same as shown in Table-1. Groundwater chemistry is taken from different regions of crystalline terrains as Visakhapatnam, A.P (SubbaRao and Krishna Rao, 1990, SubbaRao et al, 1996), Warangal district, Telangana (Ramesam et al, 1975), Gulbarga district, Karnataka (Table-2) (Krishna Rao, 1996). Dharwar schists and Deccan Traps from Gulbarga district are also included in this table as part of hard rocks.Qartz vein from Srikakulam district (VenkateswaraRao et al, 1996) is also included in this table.

Table 2: Chemical Quality of Groundwaters in Crystalline Rocks, in mg/l

S.no	Region	TDS	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	HCO ₃	CO ₃ ²⁻	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻
1	Visakhapatnam	770-820	40-51	41-56	102-183	16-18	223-264	-	182-241	39-64	-
2.	Gulburg Dt	183-3242	15-432	10-235	19-305		137-1004	0-36	18-1234	-	-
3	Dharwa Schist	564-2976	10-48	16-55	72-646		439-1004	0.24	23-371	-	-
4	-DO-Deccan Traps	252-730	24-85	13-35	15-98		173-488	0-27	16-99	-	-
5.	Warangal Dt	463	17	53	160	Trace	530	Trace	105	6	-
6.	Srikakulam Dt Gneiss	272-928	20-40	4-40	19-155	3-52	122-378	-	35-180	0-4	1-2
	Quartz vein	166-800	25-85	1-55	4-118	1-99	79-378	-	10-260	0-5	1-2
Quality Difference in Dug Wells and Bore Wells in Gneisses											
7.	Srikakula dist. Dug Well	480	40	24	30	1	171	Nil	80	20	1
	Bore Well	272	38	4	19	2	122	Nil	40	Nil	1
	Visakhapatnam Dug well	895	54	50	159	12	361	-	220	24	7
	Bore Well	496	22	24	106	5	298	-	96	16	-

Total dissolved solids in the ground waters of dug wells which pierce weathered zones is a measure of the bulk chemistry of these waters. They show a common range of 463 to 820 mg/l and exceptionally up to around 3000 mg/l. The high range of values may be attributed to local environmental conditions such as low-lying areas which influence movement of ground waters and local soil effect. Lower range of 252 mg/l is recorded in the Deccan Traps which occupy higher elevations in the area forming table land. Quartz vein contain minimum of 166 mg/l as it contains no weathered zone. Higher values in this formation is due to the effect of surface soils and clayey substance nearby. This is clear by the comparison of dug well and nearby bore well waters in Srikakulam district and Visakhapatnam district as shown in the above Table. Bore well waters which are mainly from the fracture zones at deeper levels contain relatively low TDS. Sulphates and nitrates where recorded represent contamination from the fertilisers used in agriculture fields. High chloride content, in general, correlate with high TDS but in Gulburga district, it is correlated with HCO₃ in Dharwar and Deccan Trap rocks. CO₃²⁻ is recorded in Gulburga district where Bhima (Vindhyan eqv.) formations and Deccan Traps occupy larger extent.

Chemistry of Groundwaters in Sedimentary Rocks

Quality of ground waters in the sedimentary rocks of different ages and in unconsolidated sediments is shown in Table-3. Though bulk TDS parameter may not differentiate quality, certain individual ions

can bear relation to their source rocks. Older sedimentary rocks like dolomites of Pakhals (Cuddapah eqv.system) and sullavai (Vindhyan eqv.) sandstone and shale contain higher range around 900 mg/l. Ca^{2+} and Mg^{2+} are relatively in higher range than in the crystalline aquifers. Bhima limestones and shales in Gulbarga district also contain even higher range values. calcium and Magnesium are also recorded in higher range. This may be due to poor permeability of the aquifers which restrict movement of groundwater or due to local influence of soil covers. Carbonates are recorded in Bhima limestone and shale aquifers. Sulphates are present in significant quantity in the sedimentaries of Warangal district which may be due to fertilizer impact.

Talchir tillite deposits consist of highly heterogenous sediments ranging from boulders to silt fractions in highly admixed state as it is of glacial origin. It formed high ground regionally. Therefore, TDS are at low range with 419 mg/l. Chlorides are low at 50 mg/l. Sodium is also at 38 mg/l. Calcium is high with 72 mg/l. Nearby Barakar sandstone also contain low TDS at 552 mg/l. Na^+ is in high concentration with 160 mg/l but chlorides are equal with tillite formation. HCO_3 is relatively higher with 620 mg/l. In both formations, SO_4^{2-} is recorded equally with 12 mg/l due to agriculture pollution. But SO_4^{2-} is high in Pakhals and Sullavais with 61-78 mg/l due to agricultural pollution. Carbonates are nil or in trace.

Table 3: Chemical Quality of Groundwaters in Sedimentary Rocks (mg/l)

S. no	Region	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3	CO_3^{2-}	Cl^-	SO_4^{2-}	NO_3^-
1.	Warangal Dt Pakhal(dolo)	980	168	48	125	3	330	Nil	350	61	-
2.	Sullavais, (S.st) & Shale	883	100	46	80	175	510	Trace	170	78	-
3.	Talchir tillite	419	72	22	38	2	350	Nil	50	12	-
4.	Barakar S.st	552	56	38	160	3	620	Nil	50	12	-
5.	Gulbarga Dt. Bhima l.st.	400-1600	12-187	13-111	13-388		235-604	0-54	16-1050	-	-
6.	Do -Shale	420-4666	25-220	13-118	31-839		168-497	0-24	7-1041	-	-
7.	Black Soil	1425-4636	50-160	43-131	-		183-893	-	319-1050	-	-
S. no	Region	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3	CO_3^{2-}	Cl^-	SO_4^{2-}	NO_3^-
SRIKAKULAM DT. UNCONSOLIDATED SEDIMENTS											
8.	Valley fill depo.	240-3008	15-365	1-197	5-250	0-240	79-439	-	20-890	0-9	1-2
9.	Alluvium	205-2656	5-190	1-145	5-245	0-160	91-236	-	15-890	0-75	1-2

Impact of Black Soils

Black soils (Table-3) are observed to occur as isolated patches in different parts of Gulbarga district and also in Srikakulam district in crystalline terrains. These patches represent remnants of old water bodies like tanks and lakes. These soils are evaporated residues of those waters. Groundwaters in the vicinity of these soils are invariably of poor quality with very high TDS ranging from 1425 to 4636 mg/l and chlorides from 319 to 1050 mg/l. These waters are not suitable even for irrigation. In these soils, Cl^- are more than HCO_3 indicating their concentration due to evaporation process of the water bodies.

Unconsolidated Sediments

Unconsolidated sediments like valley fill deposits and alluvium (Table-3, S.NO.8&9) show extreme conditions of quality from the best to very poor with TDS varying from 205 to 3008 mg/l and above in the both categories (VenkateswaraRao et al,op.cit). Valley fill sediments are generally ill sorted while

alluvium is well sorted sediments. It is reflected in their chemistry. Valley fill sediments relatively contain higher range of chemical constituents than the alluvium. Accordingly, cations and anions also vary. SO_4^{2-} and NO_3^- are due to agriculture (fertilizer) pollution. Higher K^+ content also confirms fertilizer pollution. Na^+ and K^+ are also recorded in the lowest concentration. Such high range of variation in chemistry can be correlated to the permeability factor which is related to the clay content in the sediments. Sand rich sediments facilitate free movement of groundwater reflected by low contents of chemical constituents. Silt and clay rich sediments restrict movement of groundwater resulting in more residence time with these constituents. Valley fill sediments distinguish in their groundwater quality with higher range of TDS, Ca^{2+} , Mg^{2+} , K^+ and HCO_3^- than in the alluvium aquifers confirming the influence of nearby hills.

Influence of Geo-environmental factors

Visakhapatnam city is developed around an arm of the inland sea over a length of about 10 Km and a width of about 3 Km. It is surrounded by hill ranges on the north, south and western sides and adjoins Bay of Bengal on the eastern side. Sea entered this valley through a gap between the hill ranges on the southeastern side. This lagoon was filled with sediments brought by a stream called Naravagedda from northwestern side. This wide central part was utilized for an inland port on the eastern side, airport in the central part and a number of chemical factories all around except the main city part on the east. Limestone was found at depth during drilling on the southeastern part. Inner beach sand was found in the city on the eastern part. These evidences confirm marine influence in this central valley of the city. Groundwaters in the city, therefore, reveals backwater effect, sea water intrusion, urban pollution and industrial pollution in different parts (Table-4), (SubbaRao et al, 1997).

Table 4: Influence of Geo-environmental Factors on Quality of Groundwaters, Visakhapatnam (mg/l)

s.no.	Environment	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-
1.	Land elevation > 15 m contour	705	37	32	191	16	193	55	3	-
2.	< 15m contour	1538	22	65	618	41	171	539	159	11
3.	Urban Pollution Dug well	1229	32	45	311	8	356	456	32	46
4.	Bore Well	506	16	28	100	5	280	89	17	-
5	Industrial Pollution Dug well	2509	60	100	610	6	329	771	529	3
6.	Bore well	2097	15	81	424	10	301	743	54	-
7.	Back Water Dug Well	1356	15	19	292	9	337	468	25	4
8.	Bore Well	510	13	6	113	6	295	95	15	trace
9.	Marine Marsh Dug Well	1640	22	79	365	9	439	576	50	3
10.	Bore well	1863	18	88	440	5	358	725	56	Trace
11.	Rain water in Visakhapatnam	60	10	1.7	8.2	0.3	12	15	2.5	-
		pH 5.75								

Land Elevation

Elevation of land also plays important role in deciding quality of groundwater as it controls its movement. Higher elevation facilitates faster movement of groundwater than the lower level by way of gradient.

In Visakhapatnam area, some parts are situated on hill slopes and their piedmont zones. Therefore, quality is compared for the ground waters in the wells located above 15 m contour are compared with the wells below that contour (SubbaRao and Krishna Rao, 1991). There is distinct change in TDS from higher contour with 705 mg/l to lower with 1538 mg/l (Table-4). Accordingly, the cations and anions also vary. Cl^- is more than HCO_3^- in the lower contour level. Higher content of Mg^{2+} than Ca^{2+} confirms

source rock as Khondalite which are garnetiferous. Lower elevation areas are mostly underlain by leptynites (gneisses) and patches of charnockites. Higher contents of SO_4^{2-} and NO_3^- indicate industrial pollution.

Urban Pollution

Urban pollution is observed in some parts of the city marked by higher content of TDS in dug wells at 1229 mg/l while bore wells contain less TDS at 506 mg/l indicating it has only surface impact. This is supported by higher values of Ca^{2+} , Mg^{2+} , Na^+ , and Cl^- in the dug wells. Confirming evidence is high content of NO_3^- with 46.1 mg/l.

Industrial Pollution

Industrial pollution is evident at places around chemical factories with high range of TDS at 2509 mg/l. Other ions also present with relatively higher range as Ca^{2+} , Mg^{2+} , Na^+ and Cl^- . SO_4^{2-} is much higher at 529.3 mg/l while NO_3^- only 2.8 mg/l. Bore well waters also contain higher values but relatively less than dug well waters. This is more conspicuous with SO_4^{2-} content which is only 54 mg/l. This constituent indicates industrial pollution and it has not yet infiltrated down significantly or it is absorbed in the soil zone.

Backwater effect

Backwater effect (tidal fluctuation) of the sea was studied in Sagarnagar colony outside the valley area adjacent to the present coast. Groundwater in the dug wells show higher TDS with 1356 mg/l while the adjacent bore wells (tapping crystalline rocks) contain low TDS with 510 mg/l. It indicates that the sea water did not percolate fracture zones probably controlled by the higher piezometric surface on the land side. Corroborative evidence is higher values of Na^+ , Mg^{2+} , and chlorides in the dug well waters than in the bore wells. SO_4^{2-} content is high in dug wells probably due to pollution effect. NO_3^- is low in dug wells and only in trace in bore wells.

Marine Marsh

Marine marsh environment inside the valley on its southeastern part in the fringe area shows higher range of TDS with 1640 mg/l in the dug wells and 1863 mg/l in the bore wells. It confirms the entire area has been contaminated with palaeo-sea water. Corroborative evidences are high values of Mg^{2+} , Na^+ , and Cl^- both in dug wells and bore wells and higher in bore wells tapping deeper fracture zones. SO_4^{2-} shows more or less same values in both the wells. NO_3^- is very low in dug wells and in traces in bore wells.

Case study -Chemistry of Rainwater at Visakhapatnam

Rainwater collected at Visakhapatnam was analysed for important chemical constituents (SubbaRao et al, 1988). pH is Conspicuously low at 5.75. Its general range is given as 6-7. It confirms air pollution from industries like oil refinery, fertilizer industry, zinc smelter, alum factory etc. TDS are 60 mg/l, its general range is given as 20 to 50 mg/l. Chlorides are at 15 mg/l. Calcium and sodium are at 10 and 8.2 mg/l respectively. Mg^{2+} is also present at 1.7 mg/l which confirms sea water effect. Sea water spray, suspended solids in the air and particulate matter in the gas emanations play important role in the rainwater chemistry. SO_4 with 2.5 mg/l confirms industrial pollution.

Iron and Arsenic Problems in Groundwaters

Groundwater from shallow tube wells at Biratnagar in eastern Nepal are found to contain iron. This area lies in the Terain plain of Khosi river province. Lithologs of shallow tube wells reveal multiple layers

of black clays at different depths alternate with grey and red clays with intermittent aquifer zones. Khosi river is known to have shifted its course by about 200 Km from Purnia. This kind of river shifting gives rise to isolated water bodies in the meanders characterized with marshy zones. Terai plain is known to have dense forest in the earlier days. Organic matter in sediments undergoes decay which create humic acids. When it is oxidized, oxygen in the sediment environment is consumed resulting in creating reducing environment. Bivalent elements like iron and arsenic converts into their low valencies. Ferric iron thus is converted into ferrous state which is soluble and hence exist in the local groundwaters. Carbon bearing sediments are characteristic with black colour. When such groundwater is pumped out, it is exposed to atmospheric oxygen and ferrous iron immediately converts into ferric state. Ferric iron is insoluble in water and hence precipitates forming sludge. It imparts red colour to the water. This sludge blocks pipelines and stains floorings. Groundwater in the aquifer is colourless but gives rustic smell (Krishna Rao et al, 1989).

Arsenic problem also has the same history as iron in its mobility. This problem is reported in parts of Gangetic plain in U.P., Bihar and West Bengal and in Jharkhand, Assam and Manipur states. It has valencies with 3 and 5. The same behavior in mobility as of iron is shown. This element creates severe health hazard.

In the case of iron problem, it is suggested that iron bearing aquifers associated with black clays may be identified and avoided. In a sedimentary basin, it is usually filled with many sequences of different sediments with repetition. Therefore, aquifers separated from such black clay horizons by one or two other colored clay beds, to avoid leakage effect also, may be chosen which are likely to contain iron free waters and exploit for public use.

Carbon-di-Oxide Problem in Dug Wells

It is sometimes reported that a person died when got into a dug well for desilting or other purpose usually during summer. A second person also meets the same fate when get into it to verify what happened. Same incident happened in a temple town near Visakhapatnam in July, 1985. The dug well was with 0.85 m diameter and 15 m deep. It was fully lined with cement as it is located on hill slope with rolled material. The area is thickly vegetated. When a lantern was lowered in to the well, the flame was put out at a depth of 5.0 m bgl. It infers the well is like gas chamber with about 10m column. The well looked clear till the bottom and there was no odour of whatsoever (Krishna Rao, 1993).

These incidents confirm existence of carbon-di-oxide dissolved in groundwaters in certain areas underlain by vegetation. As explained above, with decay of organic matter and its oxidation it becomes organic carbon. During summer, solubility of this gas is reduced as the water volume decreases due to evaporation. Then the excess gas is evolved from the water and remains in the well bottom as it is heavier than atmospheric pressure. Thus a column of gas is developed in the open well chamber. Any body who gets into it for any reason as it looks clear from outside, he is subjected to asphyxiation and meets spontaneous death. Ethane gas supports burning of lamp with popping sound. Therefore, People should be cautioned to verify presence of any gas inside dug wells which are deep by lowering a lamp.

Conclusion

The evolution of groundwater quality is governed by the interplay of geological, geochemical, hydrological and anthropogenic factors. Primary weathering reactions in the unsaturated zone release essential ions into infiltrating meteoric water, while secondary processes such as ion exchange, adsorption, and redox transformations further modify groundwater chemistry in deeper aquifers. Case studies from crystalline, sedimentary and unconsolidated terrains clearly demonstrate the role of lithology, permeability, geomorphic setting, land use, and pollution sources in shaping groundwater quality.

The study reveals that:

- Crystalline terrains exhibit moderate TDS with bicarbonate dominance, whereas sedimentary aquifers may show higher hardness or sulphates depending on lithology.
- Urban, agricultural and industrial activities significantly degrade shallow groundwater.
- Coastal and marsh environments preserve signatures of seawater intrusion or palaeo-marine influence.
- Geogenic contaminants such as Fe and As pose serious health risks in reducing aquifer conditions.
- Local geo-environmental factors such as elevation, soil type and recharge patterns greatly influence spatial variability.

Understanding these processes is essential for designing sustainable groundwater management, pollution mitigation and protection strategies.

Recommendations

To ensure safe and sustainable groundwater use, the following measures are recommended:

A. Monitoring & Assessment

1. Establish regular, long-term groundwater quality monitoring networks, especially in vulnerable regions.
2. Expand testing for geogenic contaminants (Fe, As, F) and anthropogenic pollutants (NO₃, SO₄, pesticides, heavy metals).
3. Introduce community-level water testing in rural areas.

B. Management & Protection

1. Regulate groundwater abstraction in over-exploited and coastal areas to prevent saline intrusion.
2. Promote managed aquifer recharge (MAR) using treated urban wastewater or stormwater.
3. Protect recharge areas by controlling urban encroachment and waste disposal.

C. Pollution Control

1. Strictly enforce industrial effluent standards and ensure proper treatment before discharge.
2. Promote low-input agriculture and rational fertiliser use to minimise nitrate contamination.
3. Prevent leaching from landfills, septic tanks and waste dumps through liners and improved sanitation.

D. Mitigation Measures

1. Install defluoridation, iron removal and arsenic removal units in affected areas.
2. Use alternative safe aquifers or surface-water sources where treatment is not feasible.
3. Controlled pumping from deeper aquifers avoiding intersection with contaminated horizons.

E. Research & Capacity Building

1. Encourage studies on hydrogeochemical evolution, climate impacts, and contaminant mobility.
2. Train local authorities, water managers and communities in groundwater stewardship.

Acknowledgements

The author expresses his deep sense of gratitude to Prof. A.K.Sinha, President of INC-IAH, and Vice-President, Asia, (IAH Council 2024-'28) for activating me to prepare this article

References

- Appelo, C. A. J., & Postma, D. (2005). *Geochemistry, groundwater and pollution*. Balkema, Rotterdam.
- CGWB (2023). *National Compilation on Dynamic Ground Water Resources of India*. Central Ground Water Board, Ministry of Jal Shakti.
- Clark, I., & Fritz, P. (1997). *Environmental Isotopes in Hydrogeology*. CRC Press.
- Edmunds, W. M., & Smedley, P. (2013). *Groundwater geochemistry and health: an overview*. Geological Society, London.
- Freeze, R. A., & Cherry, J. A. (1979). *Groundwater*. Prentice Hall.
- Hem, J. D. (1985). *Study and Interpretation of the Chemical Characteristics of Natural Water*. USGS Water-Supply Paper 2254.

- Krishna Rao,G.1984. Genesis of bauxite deposits of the Shevaroy hills, Tamil Nadu. Products and processes of weathering (Recent researches in Geology, Vol.II, pp98-117).Hindusthan Publishing Corporation (India).
- Krishna Rao,G. 1993. Harmful effect of Carbon- di- oxide in Dug wells. Bhujal News, CGWB, Vol. 8, pp22.
- Krishna Rao,G.1996. Influence of geo-environment on quality of groundwater, parts of Gulburga district, Karnataka State. Jour.Ind.Acad.Geosci., vol.39, pp 23-26
- Krishna Rao, G, Bhattarai,T.N, Rai,S.N, and Sharma, M.P. 1989. A Note on the Iron-rich groundwaters in the Terai plain of Morang district, eastern Nepal. Nepal Geol. Soc, Vol.6, pp13-14.
- Ramesam,V, Veeranna,M and Krishna Rao,G. 1975. Results of preliminary hydrogeological surveys in the Lower Maner basin, Karimnagar and Warangal districts, Andhra Pradesh.Proc. Indo-German workshop on Approaches and Methodologies for Development of Groundwater Resources, NGRI, Hyderabad.Pp171-189.
- SubbaRao, N and Krishna Rao,G.1991. Groundwater quality in Visakhapatnam area, Andhra Pradesh. Ind.Jour. Env.Hlth. vol. 33, pp25-30
- SubbaRao,N and Krishna Rao,G. 1990. A note on geochemistry in rocks of Eastern Ghats.Ind.Jour.Geochem. Vol, 5 (1&2), pp 49-53.
- SubbaRao, N and Krishna Rao,G, SathiBabu, Y, VenkateswaraRao,S and Suryanarayana, K. 1988. Hydrogeochemical cycle in Visakhapatnaam(A.P): Geoviews, vol. 16, pp21-26.
- SubbaRao,nPrakasaRao, J, Alisha, S.H and Krishna Rao, G. 1996. Chemical hydrogeology of an area around Visakhapatnam, Andhra Pradesh, India. 1996. Ind.Jou.Geol. Vol 68, pp 112-117.
- SubbaRao,N, PrakasaRao, j,ChandraRao,P, NiranjanaBabu, P and Krishna Rao,G. 197. Hydrogeochemical Zoning in crystalline terrain and its significance to Water quality, Jour.Geol.Soc. India, Vol.49, pp 715-719.
- VenkateswaraRao,S, Krishna Rao,G and SubbaRao,N. 1996. Factors controlling groundwater quality in parts of Srikakulam district, Andhra Pradesh. Jour. Ind.Acad. Geosci. Vol,39, pp33-39



A Critical Review of Groundwater Assessment, Estimation, and Regulatory (AER) Integration in India: Towards a Linked Framework

Nitish Kumar¹, Md Noor Uddin¹, Amit Kumar², Rambabu Singh³

¹Central Mine Planning & Design Institute Limited, Regional Institute-V, Bilaspur, India

²Government of India, Indian Administrative Service; Commissioner, Municipal Corporation, Bilaspur, India

³Central Mine Planning & Design Institute Limited, Regional Institute-IV, Nagpur, India

E-mail: nitish.kr9356@coalindia.in

Abstract

Water has been a vital natural resource in the growth of humankind, with civilizations evolving around water bodies. However, due to its ever-growing exploitation and high spatio-temporal variability in presence and availability, management of water resources has become imperative for their sustainable development. With the major burden of fresh water needs falling on groundwater, its assessment, estimation, and regulation (AER), assume prime importance. This study undertakes a comprehensive analytical review of the historical evolution and current trends of groundwater AER in India. It identifies the relationship between the Stage of Groundwater Extraction (SGWE) in high-stress assessment units and the interlinkages between draft (extraction) and regulation. Further, it proposes actionable measures to bridge existing regulatory and policy gaps. Evidently, agriculture is the largest contributor to the ground water extraction of the nation (87%) and is primarily the reason for over-exploited nature of many assessment units. However, conspicuously it is inter alia exempt from the regulation's ambit for obtaining NOC from CGWA for groundwater extraction for irrigation use, leading to the unsustainable development of groundwater resources in already over-exploited areas. Moreover, the study finds a scope for improvement in the techno-regulatory mechanisms and advocates for greater unison in AER practices. It recommends improved sectoral linkages by aligning the degree of regulation with the proportionate share of extraction across different sectors. This would promote equity and sustainability by disincentivizing unchecked groundwater use, and help arrest the decline of groundwater levels and resources, especially in high-water stress areas.

Keywords: Groundwater resource, groundwater estimation, agricultural water use, water regulations, India water policy.

1. Introduction

As a natural resource, water has played a vital role in the development of humankind. It accounts for nearly two-thirds of the Earth's surface, and makes up around three-fourths of an average human body. Historically, civilizations have evolved, thrived, and expanded around water bodies. Currently, water is a crucial factor for the growth of any economy, facilitating sectors ranging from agriculture to industry. However, water as a resource is not omnipresent and infinite. Its distribution is highly uneven: almost 97% of total water on earth resides in oceans and is unsuitable for human consumption; almost 70% of freshwater lies within glaciers and is unusable in the current scenario (Baker et al., 2016). The major burden of freshwater needs, therefore, falls on groundwater resources.

India, which is home to around 18% of the world's population and possesses only 4% of its freshwater resources (World Bank, 2023). Apart from the significant uneven distribution of water resources across countries, there is considerable variation within India as well. Around 70% of the country's ground water resource are concentrated in the Indo-Ganga-Brahmaputra plains, which constitute only 30% of India's total geographic area. Moreover, with increasing requirements for drinking water requirements

in irrigation and industries, the sustainable development and efficient management of this scarce resource is imperative.

It is in this light that a national-level estimation and assessment of groundwater resources has been taken up regularly. From the demand and utilization perspective, guidelines such as the National Building Code (NBC, 2016), guidelines to regulate and control ground water extraction in India (CGWA, 2020) have been devised, and enforced by respective regulatory authorities and updated and revised from time to time. This study undertakes a comprehensive assessment of the evolution and progress of ground water estimation and regulation in India, and concludes with suggestions based on best practices in keeping with the spirit of National Water Policy (2012).

This study analytically analyses the historical underpinnings and current trends of groundwater AER in India and identifies a linkage between the SGWE of high-stress assessment units and their draft-regulation interlinks. Further, it proposes suitable measures to bridge the linkage gap in the interest of sustainable development of groundwater resources for the country in the long-term.

2. Estimations and Assessments

2.1 Historical Ground Water Assessments

Assessment of ground water resources of the country dates back to 1949 when Dr. A. N. Khosla estimated the total average annual runoff of all the river systems of India including both surface and ground water resources, based on empirical formulae, as 167-million-hectare meter (M.ham). Since then various technical committees/ task forces have been constituted by the Government of India from time to time to estimate the ground water resources precisely. In 1976, National Commission of Agriculture assessed the total ground water resources of India as 67 M.ham and the utilizable ground water as 35 M.ham or 350 billion cubic metre (BCM) (CGWB, 1995).

In 1979, the Ground Water Over-Exploitation Committee headed by Chairman, CGWB with Members from State Ground Water Organizations and Financial Institutions, was constituted by Agriculture Refinance and Development Corporation (ARDC). The committee devised the first systematic methodology and norms to assess the ground water resources, based on which, the country's Gross Ground Water Recharge was assessed as 47 M.ham and the Net Recharge as 32 M.ham (CGWB, 1995).

2.2 Ground Water Estimation Committees

In 1982, the 'Ground Water Estimation Committee' (GEC) was constituted by the Government of India, drawing members engaged in hydrogeological studies from various Union and State organizations. The committee submitted its recommendations in 1984 and suggested a methodology for the assessment of dynamic groundwater resources, which is commonly referred to as GEC-1984. As per the recommendations of GEC-1984, State Governments constituted High-Level Working Groups, convened by Director, CGWB, and comprising of Heads and In-charges of Groundwater Departments, inter alia, for assessment of respective ground water potential. With the base year for the computation of resource varying between 1991 and 1993, a National report on Ground Water Resources of India was brought out in 1995 by compiling the data of all the States and Union Territories. As per the report, the total replenishable ground water in India was assessed as 432 billion cubic meters (BCM). The ground water resource available for irrigation purpose was about 361 BCM and the Net ground water draft for irrigation uses was about 115 BCM; therefore, the overall level of Ground Water Development was worked out as 32% (CGWB, 1995).

Increasing thrust on ground water and improved data acquisition techniques led the Government of India to form another Committee in 1995 to review the existing methodology for ground water resource assessment and to suggest revisions, if necessary. The committee submitted its report in 1997 and suggested a revised and elaborate methodology for resource assessment, commonly referred as GEC-1997. In 2001, another committee on ground water estimation methodology in hard rock terrain was formed to overcome the limitations of ground water assessment in crystalline terrain/ fissured

formations. The committee made suggestions on the criteria for categorization of blocks to be adopted for the entire country irrespective of the terrain conditions.

The GEC-1997 guidelines, initially adopted for national assessments, were largely empirical and applied at the administrative block level. Recognizing the need for refinement, the GEC-2015 methodology introduced comprehensive revisions, incorporating aquifer-wise assessments, improved recharge and discharge estimation techniques, and the integration of remote sensing and GIS tools. This transition marked a shift towards more realistic and dynamic groundwater resource evaluations. Building on this, the upcoming GEC-2023 methodology retains the technical framework of GEC-2015 but proposes a significant change in the classification system of groundwater assessment units. The new classification aims to align with emerging priorities such as aquifer sustainability, climate resilience, and more nuanced policy interventions, while maintaining the robust estimation processes introduced in GEC-2015.

2.3 Ground Water Estimation Methodology

Groundwater Estimation methodology is based on the Water Balance Theory. Various input and output components of ground water balance are computed to estimate the Ground Water Recharge. The Ground Water Draft is estimated based on two basic approaches recommended by the GEC - 1984, namely ground Water Level Fluctuation method and Rainfall Infiltration Factor method. The assessment unit is thus categorized based on the percentage of ground water development with respect to ground water recharge.

The principal attributes of the currently being followed GEC-2015 guidelines are as follows: Aquifer-wise ground water resource assessment of both the groundwater resources components, i.e., Replenishable ground water resources or Dynamic Ground Water Resources and In-storage Resources or Static Resources are to be undertaken. For the unconfined aquifer, wherever the aquifer geometry has not been firmly established, the in-storage ground water resources must be assessed down to the depth of bed rock or 300 m, whichever is less, in the alluvial areas, and up to a depth of 100 m in case of hard rock aquifers. For the confined aquifers, if it is known that groundwater extraction is being done from such aquifer, the dynamic as well as in-storage resources are to be estimated. If it is firmly established that no ground water extraction is being undertaken from a certain confined aquifer, then only the in-storage resources of that aquifer has to be estimated. Until the aquifer geometry is established on an appropriate scale, the practice of using watershed in hard rock areas and blocks/*mandals* in soft rock areas may be continued.

However, an inherent limitation remains, which the GEC-2015 guideline also admits: “Presently there is no fine demarcation to distinguish the dynamic resources from the static resources.” Moreover, while the guideline specifies separate assessment techniques for Dynamic and Static ground water resource, distinguishing the two components in the extraction estimations remains a grey area, especially for deep abstraction structures. Hence, the overall assessment equates separate dynamic and static components on the resource front with extraction from a mix of static and dynamic resource.

2.4 Groundwater Assessment Trends

From 2017 onwards, GEC-2015 methodology is being followed for national level assessment of groundwater resources by Central Ground Water Board (CGWB) - the national agency under Ministry of Jal Shakti for assessment, management and development of ground water resources in the country, some significant trends based on these assessments are discussed below.

The trends in Annual Ground Water Recharge, Annual Extractable Ground Water Resource, Annual Ground Water Extraction for Irrigation, Domestic and Industrial uses (BCM) and Stage of Ground Water Extraction (%) of assessment from 2017 to 2024 are charted in the Figure 1 (CGWB, 2024).

As evident from the trends, the Annual Extractable Ground Water resources have been increasing while the Annual Ground Water Extraction for various uses has been overall slightly decreasing, thus leading to improvement in the Stage of Ground Water Extraction over this period. This is a reflection of a

combination of factors at interplay: increasingly accurate Hydrogeological data collection and computations, growing body of rainwater harvesting and groundwater recharge initiatives by various stakeholders, coupled with decreasing extraction of groundwater and increasing utilization of surface water sources.

As per the 2024-Assessment, the total Annual Ground Water Extraction of the entire country has been estimated as 246 bcm. The agriculture sector, accounting for 87% of the total groundwater extraction (213 BCM), is the largest consumer of groundwater resources, followed by domestic use accounting for 11% (28 BCM) and industrial use making up 2% (4 BCM) of total annual groundwater extraction (Figure 2). This depicts a highly skewed pattern of Groundwater Extraction with a large majority being for Irrigation Use and a comparatively minor quantum being extracted for industrial use.

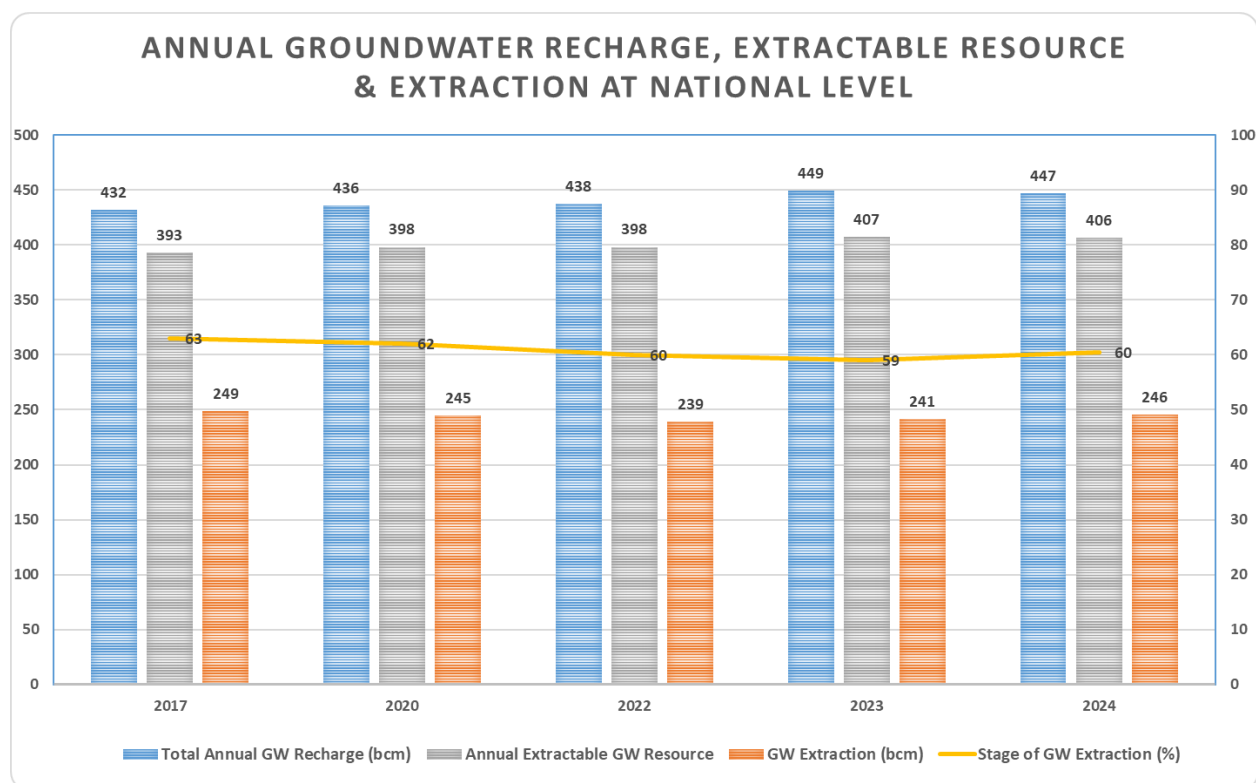


Figure 1: Trends of Ground Water Resource Assessments.

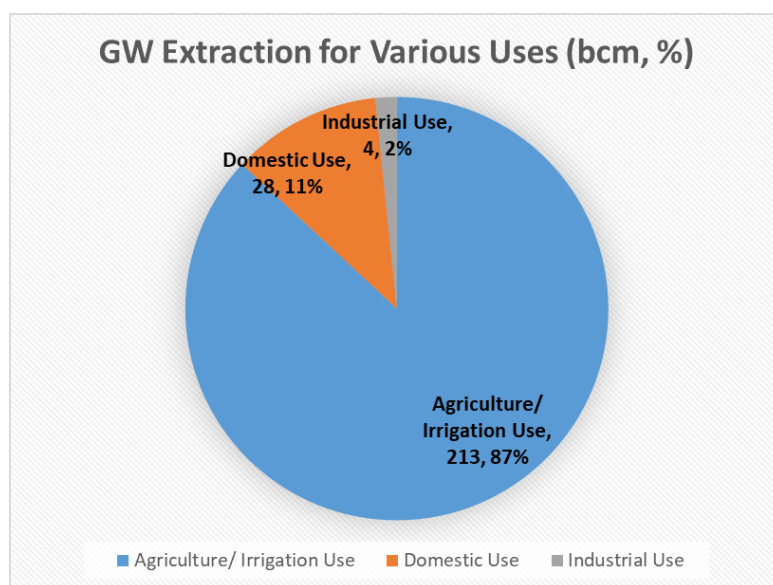


Figure 2: Ground Water Extraction estimated for various uses (2024).

On study of Categorization of Assessment Units for the country in the Ground Water Resource Assessment (CGWB, 2024): around 73% (4951 units) of the 6746 total assessed units are found to be in Safe category, 11% (711 units) are Semi-Critical, 3% (206 units) are Critical, 11% (751 units) are Over-Exploited, while 2% (127 units) fall in Saline category (Figure 3- 4). The Stage of Ground Water Extraction is high in north-western states of Haryana, Punjab, Rajasthan with most of their blocks falling in Over-Exploited category.

Evidently, the ground water resources of certain states are under much higher pressure than the rest, and that the Stage of Ground Water Extraction shows large spatial variation in the country. Moreover, Hilly states like Uttarakhand, Himachal Pradesh, and coastal states like Andhra Pradesh lack appropriate hydrogeological data.

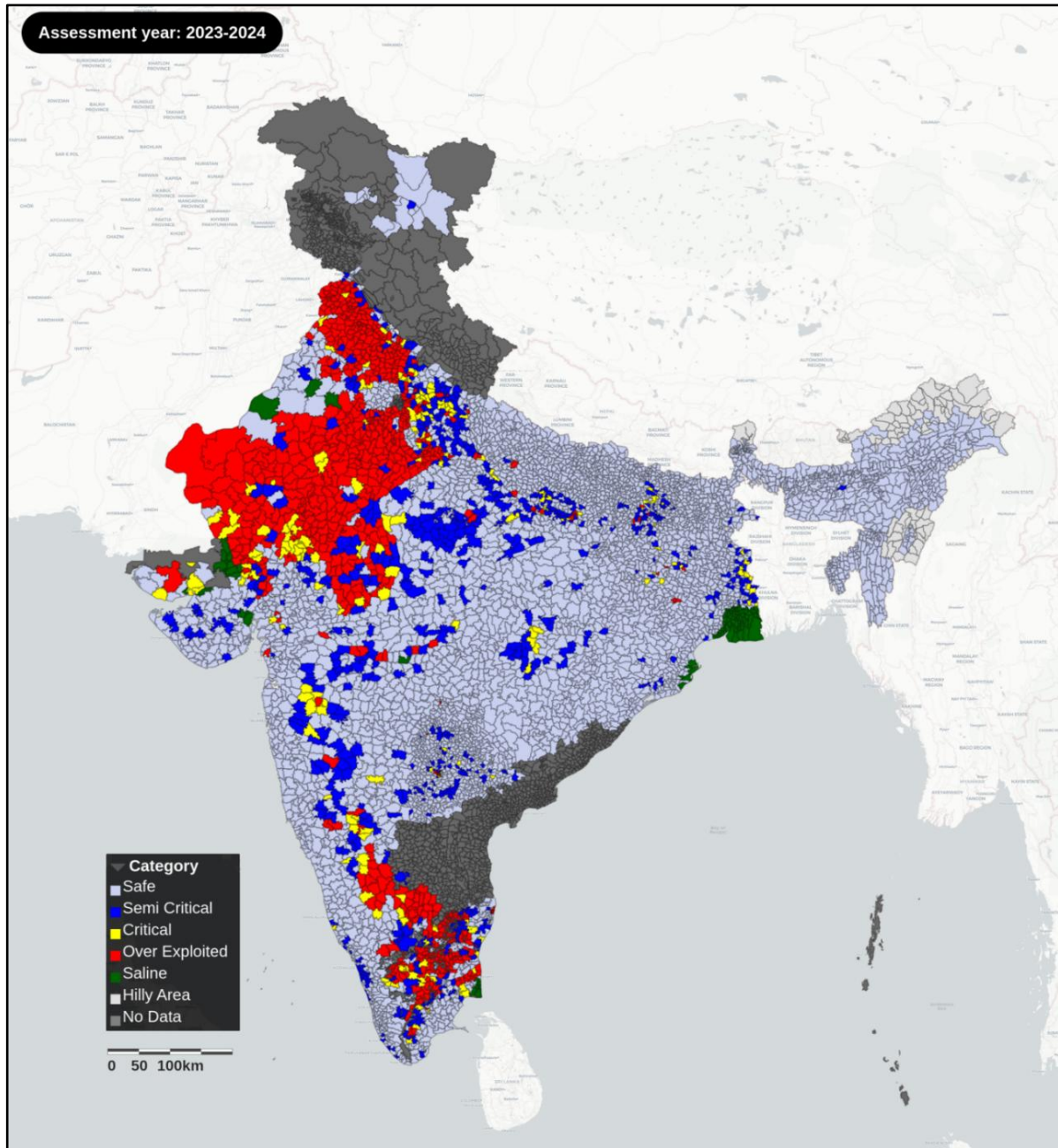


Figure 3: Categories of Assessment Units based on Stage of Ground Water Extraction (Map based on: INGRES portal).

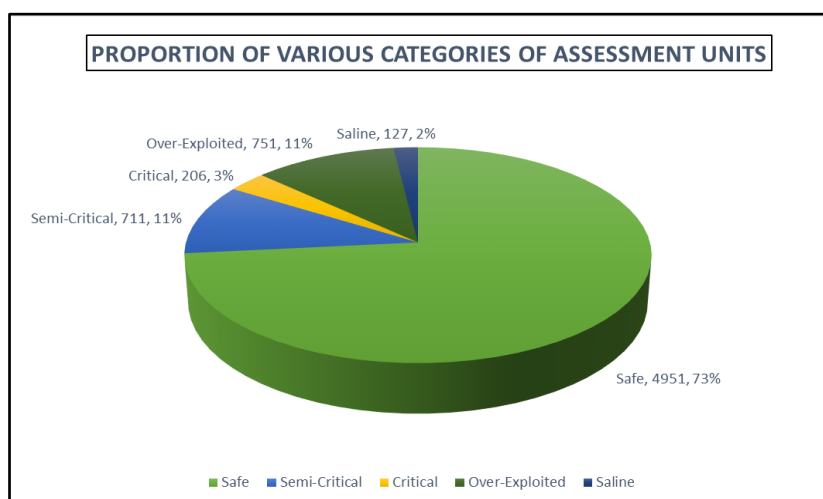


Figure 4: Proportions of various Categories of Stage of Ground Water Extraction in India (2024).

3. Ground Water Regulation in India

In India, water is a State List subject under Seventh Schedule to the Constitution, and the legislation for regulation and development of ground water is to be enacted by the State Governments/ Union Territories (UTs). However, the regulation of ground water abstraction/ utilization is being done both at Union and State levels. The Department of Water Resources, River Development and Ganga Rejuvenation (DoWR,RD&GR) is allocated with overall planning and policy making for the development of ground water resources. In pursuance of the orders of the Hon'ble Supreme Court (1996), the Central Ground Water Authority (CGWA) was constituted in 1997 under Section 3(3) of the Environment Protection Act, 1986 for the regulation and control of ground water management and development. CGWA is regulating the States and UTs in the country except for 16 States/ UTs which are not regulated by it (as of September 2024); the regulation of groundwater development and management in these states is being done through constitution of State Ground Water Authority or government orders (NOCAP portal).

CGWA releases guidelines for ground water abstraction from time to time. As per the CGWA Guidelines-2012, only new units and industry, infrastructure and mining projects seeking expansion fell under the purview of the guidelines. In the revised guidelines of November 2015, all existing industries/ projects which were drawing ground water and had not obtained NOC from CGWA were also required to apply to CGWA with immediate effect for NOC for ground water withdrawal. Under the November 2012/ November 2015 guidelines, CGWA had notified 162 critical/ over-exploited areas for the purpose of regulation of ground water development. In the notified areas, ground water abstraction was not permissible for any purpose other than drinking and domestic use. In the non-notified areas, CGWA could permit extraction of ground water for industrial/ infrastructural/ mining projects.

In pursuance of the directions of the Hon'ble National Green Tribunal (NGT), CGWA notified revised guidelines in September 2020. The new guidelines now have Pan-India applicability and will prevail in case of any difference with the States' guidelines. Some of the earlier provisions such as notification of areas by CGWA have been dispensed with, while some new provisions, such as differential charges for extraction of ground water in different categories of areas have been introduced (CAG, 2021).

The regulatory guidelines for groundwater development, thus, have grown more comprehensive over time with continuous revisions and amendments. A noteworthy aspect signifying the growing scope and scale of regulation is the introduction of mandatory groundwater numerical flow modeling studies along with the application for ground water abstraction, depending on the abstraction quantum over respective specified limits for areas of various categories (CGWA SOP v9.1, May 2023).

However, a major fact that needs to be taken cognizance of is that the sector accounting for the largest majority (87%) of annual ground water extraction is exempt from the purview of CGWA guidelines. As

per Section 1(i) of the CGWA Notification of Sept 2020, agricultural activities are exempt from seeking No Objection Certificate from CGWA (CGWA Notification, September 2020). Evidently, most of the Over-Exploited assessment units fall in the north-western states where ground water extraction for agricultural use is high. Hence, in keeping with the analytical jurisprudence for sustainability of groundwater resources, there is a scope for better alignment of regulation of various sectors with their respective proportion in the overall groundwater extraction. Agriculture should be brought in the ambit of groundwater regulations, especially in the Over-Exploited, Critical and Semi-Critical (OCS) blocks. However, to ensure farmer welfare, those transitioning from water-intensive to less water-demanding crops should be incentivized through Minimum Support Price (MSP) mechanisms. This approach will aid in curbing groundwater depletion in OCS blocks while simultaneously enhancing farmer awareness and promoting sustainable water use practices.

4. Ground Water Policy and its Future

In line with the aspirations of a flourishing economy, sustainability of resources and environmental protection, the Government of India has brought about Water Policies from time to time. The National Water Policy, 1987 suggested the assessment of groundwater on scientific basis, while highlighting the need for conjunctive use of both surface water and groundwater (MoWR, 1987). The National Water Policy, 2002 highlighted the need to regulating groundwater resources and prevention of over exploitation so that overuse does not exceed recharging limits, however, it focused more on surface water management rather than groundwater management (MoWR, 2002). The National Water Policy, 2012 focuses on managing groundwater as a community resource by the State under the principle of public trust doctrine to achieve complete food security and sustainable management of groundwater. It also recommends the conjunctive use of surface water should be with both rainwater and groundwater, and further focuses on separation of electricity supply for pumping groundwater for agricultural and other rural uses (MoWR, 2012).

For the Water Policies to have better desired effect all throughout the country, water as a subject can be transferred to the Concurrent List with both Union and the States having jurisdiction over its regulation. The precedent for such a shift was already set by the Constitution (Forty-second Amendment) Act, 1976 which was passed after the 1972 United Nations Conference on the Human Environment. By the Section 57 (c) (ii) of the Act, the entries “Forests” and “Protection of wild animals and birds” were inserted in the Concurrent List as part of facilitating Environmental Protection measures at the national level (National Portal of India). With growing realization of water as a resource, just like Environment half a century back, national-level regulation of water resources needs to be strengthened to deal with regional disparity. Such a change for Water will also reflect the fact that occurrence and flow of water is bounded not by administrative boundaries but watershed boundaries, and needs to be regulated as such.

5. Conclusion and Suggestions

Keeping in view the growing importance of groundwater as a natural resource, and complexities due to its spatial and temporal availability, it can be concluded that Ground Water Assessment, Estimation and Regulation need to function in unison and not as silos. While the assessment of ground water resources is necessary to gauge the ground truth situation, it needs to gradually and continuously be expanded in scope and coverage to also take into consideration other elements like base flow, information on quality of ground water along with its quantity. Estimation methodology needs to be continuously revised with latest and upcoming scientific and technical developments such as using ground water flow and solute transport numerical modeling to verify and supplement the assessments undertaken, taking up groundwater estimation at watershed level as opposed to limiting the assessment units to block-level.

In the larger interest of sustainable development and management of groundwater resources in the country, Proportionate Regulation needs to be undertaken. That is to say, the regulation policy must be based on and in sync with the estimation-derived assessment data. The extent of regulation on each sector should be kept proportionate to their relative impact or quantum of extraction they undertake in the total extraction for all uses. For example, since agricultural activities account for 87% of total groundwater extraction and subsequently lead to significant depletion in groundwater resources, practical regulatory mechanisms need to be charted out to bring them within the purview of groundwater

regulation. These may include measures like disallowing exemptions from obtaining NOC in OCS areas, large farmlands over a certain threshold area of landholding being irrigated from groundwater. However, any such regulation on groundwater extraction for agricultural activities would also need to be based on local-scale considerations like agro-climatic zones, cropping patterns, and socio-economic development and needs of the concerned communities.

The Water Policy itself needs to evolve into more comprehensive vision for sustainable development of surface and groundwater resources of the country. This could include factoring in the benefits of the techno-legal exercise of moving water as a subject to the “Concurrent List” in line with it being a natural and national resource. Last but not the least, the trinity of Assessment-Estimation-Regulation (AER) should form a feedback mechanism within themselves for optimum efficiency and operate within the larger framework of the National Water Policy, which would be shaped by growing socio-economic aspirations of the nation, and international considerations like globally rising water scarcity- in terms of both water quality and quantity.

Acknowledgements

We express our sincere and deep sense of gratitude towards Mr. Manoj Kumar, Regional Director, and Mr. Syamantak Chatterjee, HOD (Exploration), CMPDI, RI-V, Bilaspur for their overall guidance; and to Mr. R. K. Singh, GM (Exploration), and Mr. Debasis Bandhopadhyay, Technical Head, Hydrogeology Division, CMPDI (HQ), Ranchi for their support.

References

- Baker, Beth & Aldridge, Caleb & Omer, Austin. (2016). Water: Availability and use. Mississippi State University Extension. 2016. p3011.
- CAG (2021) Report of the Comptroller and Auditor General of India on Ground Water Management and Regulation, Report No. 9 of 2021
- CGWA (2020) Guidelines to regulate and control ground water extraction in India, Gazette Notification S.O. 3289(E)
- CGWB (1995) Report on Ground Water Resources of India
- CGWB (2023) National Compilation on Dynamic Ground Water Resources of India
- CGWB (2024) National Compilation on Dynamic Ground Water Resources of India
- CGWB, INDIA-Groundwater Resource Estimation System (IN-GRES) portal, <https://ingres.iith.ac.in/home> (as on 24th September 2024, 12:30 PM IST)
- CGWA, NOCAP Portal, NOC to Abstract Ground Water, <https://cgwa-noc.gov.in/LandingPage/GroundWater.htm> (as on 25th September 2024, 1:30 PM IST)
- CGWA, SOP v9.1 (May 2023) Standard Operating Procedure for Implementation of MOJS Guidelines and Amendments Thereof
- MoWR/ Ministry of Jal Shakti, National Water Policy (1987), <https://164.100.94.100/sites/default/files/National%20Water%20Policy%201987%20English.pdf> (as on 25th September 2024, 4:30 PM)
- MoWR/ Ministry of Jal Shakti, National Water Policy (2002), https://164.100.94.100/sites/default/files/nwp20025617515534_1.pdf (as on 25th September 2024, 4:30 PM)
- MoWR/ Ministry of Jal Shakti, National Water Policy (2002), https://164.100.94.100/sites/default/files/NWP2012Eng6495132651_1.pdf (as on 25th September 2024, 4:30 PM)
- National Portal of India, The Constitution (Forty-second Amendment) Act, 1976, <https://www.india.gov.in/my-government/constitution-india/amendments/constitution-india-forty-second-amendment-act-1976> (as on 25th September 2024, 4:45 PM)
- World Bank (2023), How is India addressing its water needs? <https://www.worldbank.org/en/country/india/brief/world-water-day-2022-how-india-is-addressing-its-water-needs> (as on 25th September 2024, 5:00 PM)



Impact Assessment Study on Groundwater levels in part of the States of North East India

S. Somarendro Singh

Central Ground Water Board, North Eastern Region, Guwahati, Assam, India 781035

E-mail: sss153@rediffmail.com

Abstract

The design of Pradhan Mantri Krishi Sinchayi Yojana – Har Khet Ko Paani- Ground Water Irrigation envisages to provide assured ground water irrigation to small and marginal farmers having agriculture land up to 2 hectares without any facility of irrigation and the area have sufficient potential for future development of ground water for irrigation purpose. Under these projects, a total of 12829 numbers of irrigation wells have been constructed with the creation of 48745 hectares of command area by benefitting 49074 numbers of farmers in six states of North East India, namely, Assam, Arunachal Pradesh, Manipur, Mizoram, Nagaland and Tripura during 2019-20 to 2022-23. This paper basically aims whether there is any significant change or decline in the groundwater level of these project areas where the schemes being utilised the dynamic groundwater resources through shallow tube wells and dug wells. It has been observed that there is no significant change/decline of groundwater level in most of the scheme sites and area due to withdrawal of groundwater for irrigation under this scheme. Rainfall is good enough for substantial annual recharge of the groundwater aquifer, thereby maintaining the ground water level in stable condition. Further, the annual recharges from the canals, rivers, check dams and other surface sources etc. also contribute significantly for groundwater recharge. This is clearly substantiated by the reports of Dynamic Ground Water Resource, 2020, 2022, 2023 and 2024 which suggest that the ground water scenario in north eastern states are falls under safe category. Moreover, sustainable development groundwater in those water logging areas may help in the management sector.

Keywords: groundwater irrigation, marginal and small farmers, dynamic groundwater resource, sustainable development, shallow aquifer

Introduction

Pradhan Mantri Krishi Sinchayi Yojana (PMKSY) was formulated with the vision of extending the coverage of irrigation ‘Har Khet Ko Paani (HKKP)’ in a focused manner with a component of Ground Water for creating additional irrigation from ground water resources in areas, where ground water is sufficiently available. It has also planned to enhance small and marginal farmer’s income in such areas by providing assured irrigation facility under the scheme. The scheme effectively launched in 2019-20 after revision of guidelines by giving priority in holistic and sustainable development of irrigated agriculture based on scientific approaches. The scheme envisages to provide ground water irrigation to only small and marginal farmers (up to 2 hectares of land area) who does not have any facility of irrigation and the area have sufficient potential for future development of ground water for irrigation purpose. Priority has also been given to scheduled caste / scheduled tribe and women farmers.

Groundwater irrigation facility through dug wells, dug cum bore wells, tube wells, and bore wells are specially for the areas other than over exploited (OE), critical or semi-critical meeting the following criteria:

- a. Less than 60 per cent of the annual replenishable ground water resources have been developed.
- b. Average annual rainfall of 750 millimetre (mm) or more to have availability of enough water for recharge;
- c. Shallow ground water levels within range of 15 metre below ground level (mbgl) or less during pre-monsoon period.

As part of the energization, each successful well was provided with electric/solar pumps for water lifting. Provision of 75% electric pumps and 25% solar pumps have been considered for a cluster of proposal. Consideration and relaxations have been made in the ratio of solar pumps specially in tribal/left wing extremism (LWE)/ infested/difficult areas. Further, wherever electric power is not available, the whole scheme was permitted with Solar pumps with prior permission with Government of India.

Implementation of the Scheme

Based on the findings and management plan of NAQUIM 1.0 of Central Ground Water Board, scope of groundwater development for irrigation under PMKSY-HKGP-GW, a flagship scheme under Department of Water Resources, River Development & Ganga Rejuvenation, Ministry of Jal Shakti, Government of India have been implemented in six states of north east India during the financial years 2019-20, 2020-21, 2021-22, and 2022-23. A total of nine groundwater irrigation schemes have been implemented in the states of Assam as Phase-I & Phase II, Arunachal Pradesh as Phase-I & Phase II, Tripura as Phase-I & Phase II, one phase each in Nagaland, Manipur, and Mizoram.

Under these projects, a total of 12829 numbers of irrigation wells have been constructed with the creation of 48745 hectares of command area by benefitting 49074 numbers of farmers in six states of North East India, namely, Assam, Arunachal Pradesh, Manipur, Mizoram, Nagaland and Tripura during 2019-20 to 2022-23.

Table 1: State wise break up of implementation of PMKSY-HKGP-GW schemes

Components	Assam	Arunachal Pradesh	Manipur	Mizoram	Nagaland	Tripura	Total
	Phase I & II	Phase I & II	Phase I	Phase I	Phase I	Phase I & II	
Cost of projects (crore)	538.08	90.25	61.68	16.04	18.15	61.65	785.85
Wells Construction (Nos)	9695	992	550	209	262	1121	12829
Command area created (ha)	38648	3742	2057	553	667	3077.8	48745
Numbers of farmers benefitted (nos.)	36843	6983	1445	422	264	3117	49074

Materials and Method

Water level data from the Ground Water Regime Monitoring Stations of CGWB, NER located in different districts where PMKSY-HKGP-GW scheme was implemented were collected for a detail analysis of pre-monsoon and post-monsoon changes, trends etc. Data was collected for the implementation period of the scheme, i.e., for the years 2020, 2021, 2022, 2023 and 2024. Further, analyses of change in the annual recharges from rainfall, recharge from other sources, like, annual recharge from canals, rivers, check dams and other surface sources etc. also showed contribution to ground water recharge. This is clearly substantiated by the reports of dynamic ground water resources, 2020, 2022, 2023 and 2024 which suggest that the ground water scenario in north eastern states are falls under safe category.

Results and Discussion

Ground water regime monitoring in the states of North East India

Central Ground Water Board, North Eastern Region has set up several ground water monitoring stations (GWMS) in different hydrogeological conditions to know ground water condition and its variation, in both time and space. Monitoring of water levels and collections of water samples are being carried out periodically to observe any change in water level and its quality consequent to changes in inputs and outputs. To have an idea of water level behavior with respect to time, water levels are being monitored four times a year.

The rainfall is the main source of ground water recharge in North Eastern Region. The annual average rainfall in the region varies from 900 mm to more than 5000 mm. Geologically, the area is underlain by consolidated to unconsolidated formations ranging in age from Archaean to Recent in age.

Hydrogeologically, the area is grouped into porous and fissured formations based on the nature of openings in the aquifer system. Alluvium and sedimentary formations and fissured consolidated rocks form the main repositories of ground water. Water levels in the region remain mostly within 5.00 mbgl in all four occasions of periodic monitoring.

Results of ground water regime monitoring in areas/districts where PMKSY-HKGP-GW schemes were implemented

Water level monitoring data from ground water regime monitoring (GWMS) stations of NER located in the districts where PMKSY-HKGP-GW scheme was implemented were collected for a detail analysis of water level conditions during pre-monsoon and post-monsoon for the implementation period of the above scheme, i.e., for the years 2020, 2021, 2022, 2023 and 2024. The pre-monsoon and post-monsoon water level data is given below in Table 2.

Table 2: Pre-monsoon and post-monsoon water level data in PMKSY-HKGP-GW scheme districts

State	District	Pre-monsoon Depth to Water Level (mbgl)				
		Mar 24	Mar-23	Mar-22	Mar-21	Mar-20
Arunachal Pradesh	Changlang	4.60	5.10	4.83	3.40	4.20
	East Siang	6.01	6.02	5.75	5.99	5.28
	Lohit	3.23	4.55	5.55	4.88	3.25
	Lower Dibang valley	4.71	3.86	4.73	4.58	4.51
	Papum Pare	3.35	3.91	3.54	3.87	3.12
	Tirap	4.95	5.13	5.65	6.04	6.34
Assam	Baksa	5.93	4.95	6.33	6.76	6.23
	Arpita	2.96	3.42	2.80	3.57	4.23
	Biswanath	4.30	4.17	4.23	4.16	4.39
	Bongaigaon	4.32	3.85	3.89	4.36	4.62
	Cachar	2.79	2.57	3.22	3.63	3.46
	Darrang	5.02	5.52	5.73	4.50	5.02
	Dhemaji	3.21	3.31	3.23	3.22	3.38
	Dhubri	7.95	7.64	8.88	7.23	8.88
	Dibrugarh	3.57	3.20	3.87	4.40	3.89
	East Karbi Anglong	5.21	5.97	5.46	2.10	6.54
	Goalpara	4.2	4.0	3.6	3.39	4.70
	Golaghat	5.38	6.89	6.50	5.86	5.43
	Hailakandi	4.07	2.22	3.85	3.30	2.04

	Hojai	5.95	4.78	5.06	5.74	4.84
	Jorhat	3.27	2.44	2.11	2.18	2.39
	Kamrup	4.78	3.61	3.83	3.41	3.66
	Kamrup Metro	2.45	2.01	2.27	3.15	1.69
	Karimganj	1.54	2.21	1.68	1.91	2.02
	Kokrajhar	4.37	4.19	4.00	4.16	6.22
	Lakhimpur	2.85	2.98	2.83	2.88	2.85
	Morigaon	4.33	3.76	4.60	3.61	3.56
	Nagaon	3.65	2.80	2.97	3.17	3.08
	Nalbari	2.67	3.01	2.85	3.68	6.45
	Sibsagar	5.53	3.71	5.48	5.36	4.94
	Sonitpur	3.62	3.89	3.86	3.35	3.47
	Tinsukia	3.67	3.89	4.24	3.74	4.22
	Udalguri	3.45	3.65	3.21	2.72	2.63
	West Karbi Anglong	5.44	4.90	4.55	4.97	4.80
Nagaland	Dimapur	5.08	4.48	6.35	6.49	6.35
	Mokokchung	0.738	No data	No data	No data	No data
	Mon	2.84	No data	No data	No data	No data
	Wokha	3.26	No data	No data	No data	No data
Tripura	Dhalai	4.03	4.17	3.99	3.81	4.02
	Gomti	4.70	5.29	4.60	4.11	4.57
	Khowai	3.85	5.21	5.38	5.04	5.75
	North Tripura	3.11	3.37	3.65	3.39	3.56
	SipahiJala	3.36	3.90	3.22	2.95	3.02
	South Tripura	5.60	5.33	4.91	5.17	5.21
	Unakoti	4.62	5.12	5.18	4.89	4.71
	West Tripura	7.00	8.30	7.91	9.57	12.03

Result of Analysis

It has been observed that there is no significant change/decline of groundwater level in most of the scheme sites and area due to withdrawal of groundwater for irrigation under PMKSY-HKGP-GW scheme. Rainfall is good enough for substantial annual recharge of the groundwater aquifer, thereby maintaining the ground water level in stable condition. Further, the annual recharges from the canals, rivers, check dams and other surface sources etc. also contribute significantly for groundwater recharge. This is clearly substantiated by the reports of dynamic ground water resource (GWRE), 2020, 2022, 2023 and 2024 which suggest that the ground water scenario in north-eastern states are falls under safe category. Moreover, sustainable development groundwater in those water logging areas may help in the management sector by developing such groundwater irrigation schemes for the deprived farmers. The followings are district-wise pre-monsoon and post-monsoon depth to water level trends in the monitoring station of scheme area.

Table 3.a. Pre-monsoon depth to water level trend for years 2020 to 2024 in PMKSY-HKGP-GW implemented districts of Arunachal Pradesh

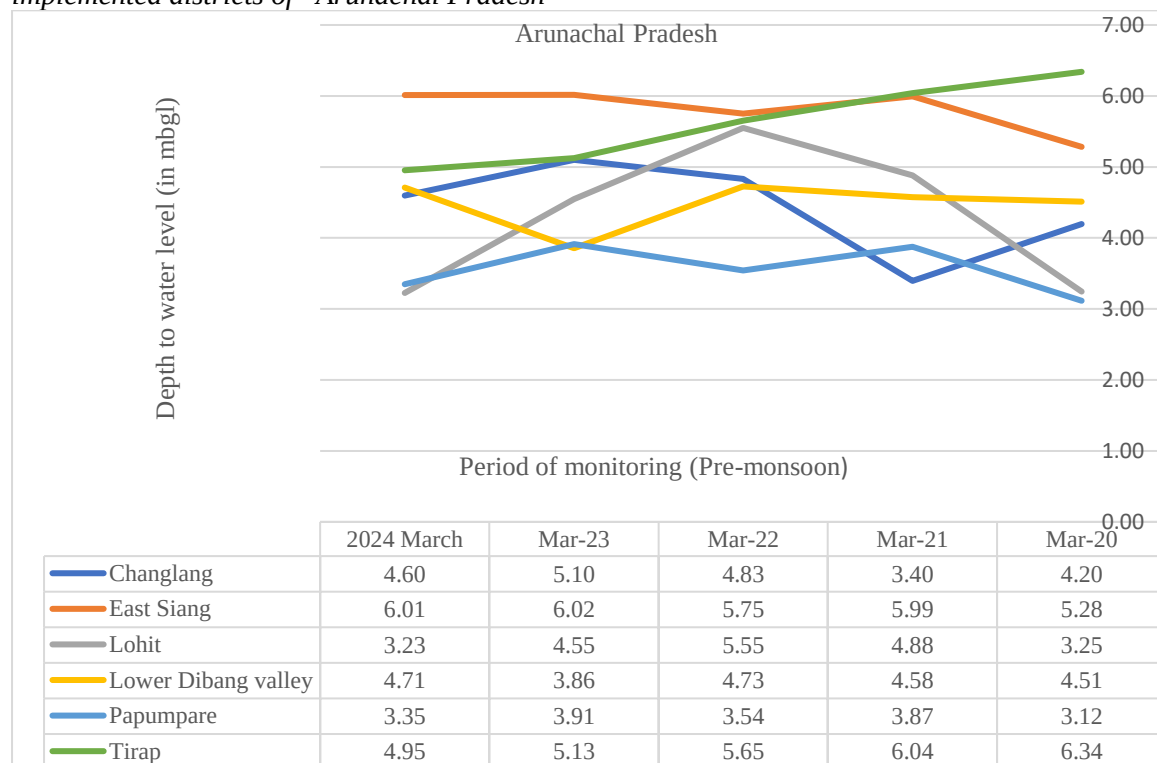


Table 3.b. Post-monsoon depth to water level trend for years 2020 to 2023 in PMKSY-HKGP-GW schemes implemented districts of Arunachal Pradesh

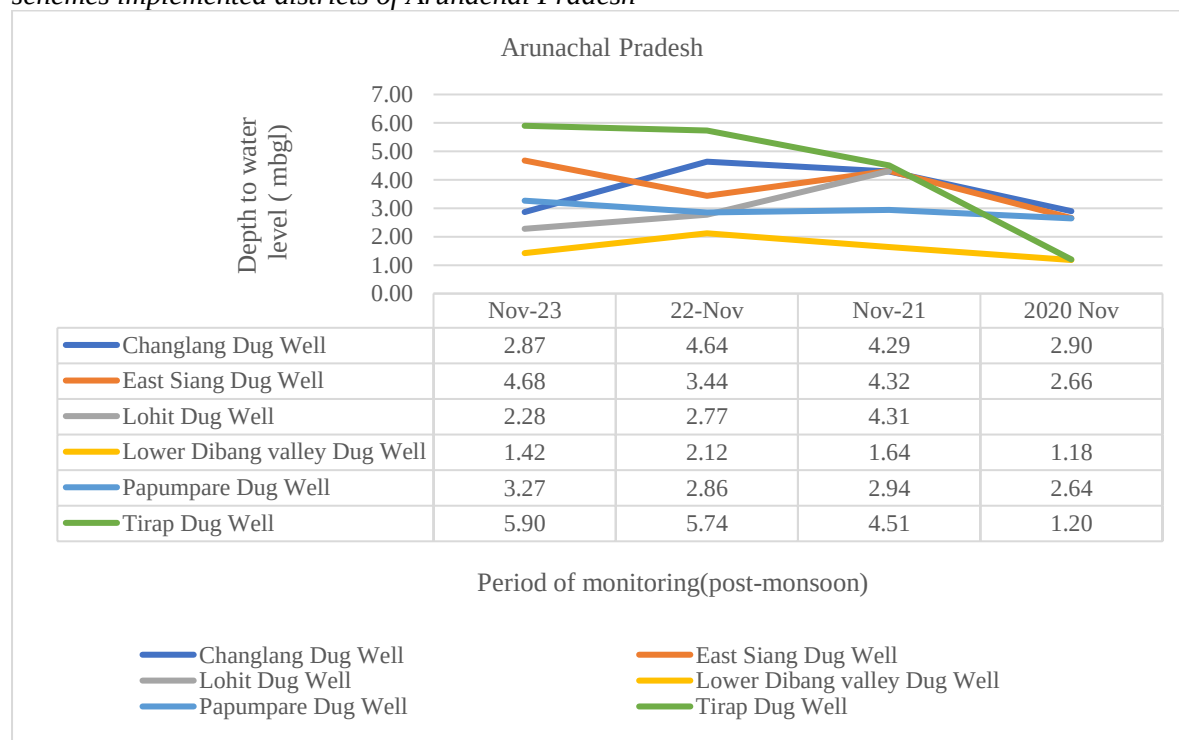


Table 4.a. Pre-monsoon depth to water level trend for years 2020 to 2024 in PMKSY-HKGP-GW schemes implemented districts of Assam

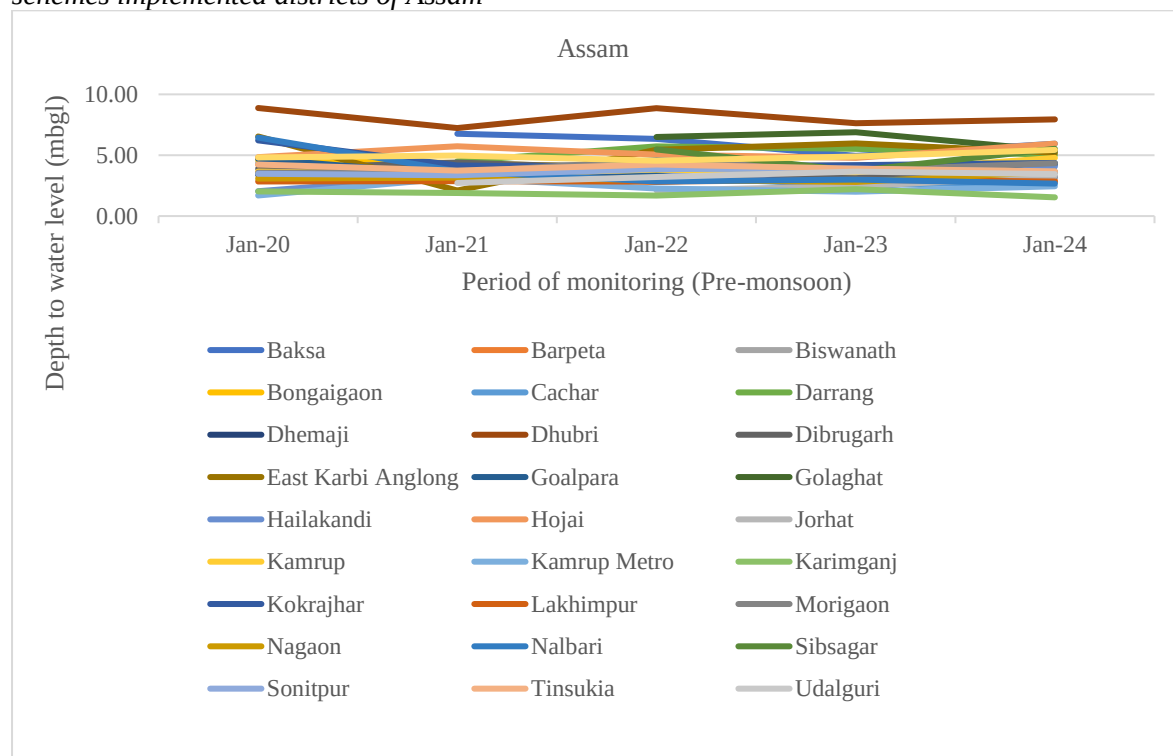


Table 4.b. Post-monsoon depth to water level trend for years 2020 to 2024 in PMKSY-HKGP-GW schemes implemented districts of Assam

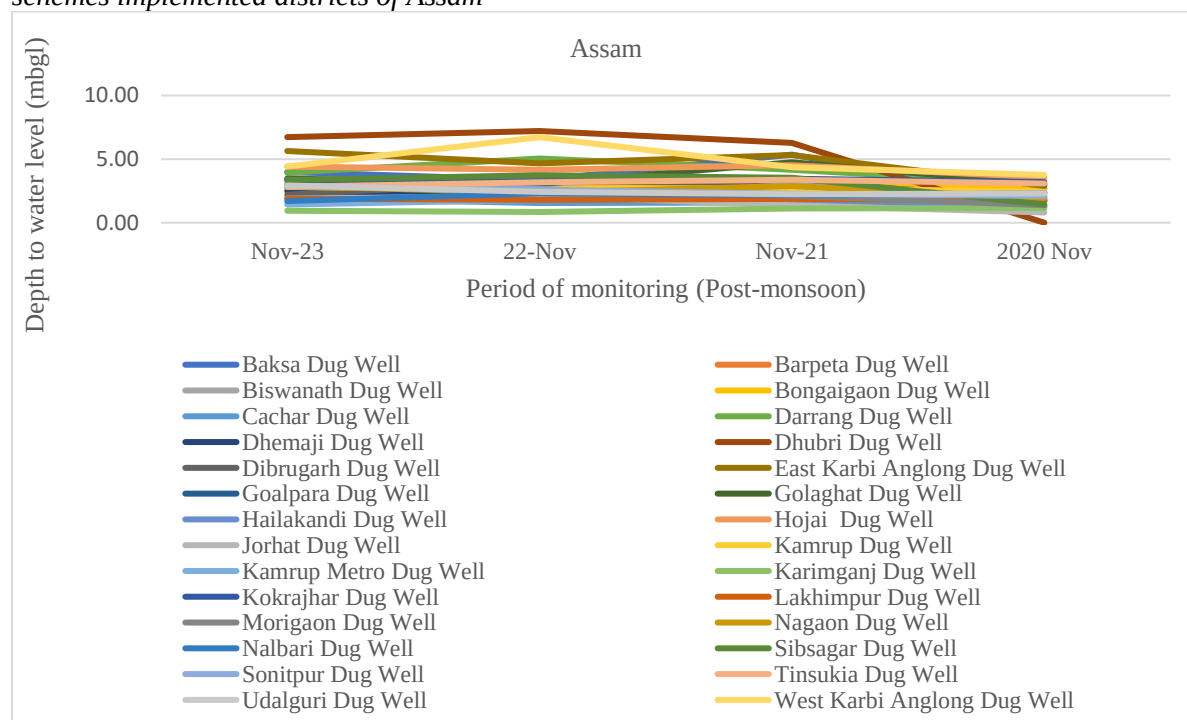


Table 5.a. Pre-monsoon depth to water level trend for years 2020 to 2024 in PMKSY-HKGP-GW schemes implemented districts of Tripura

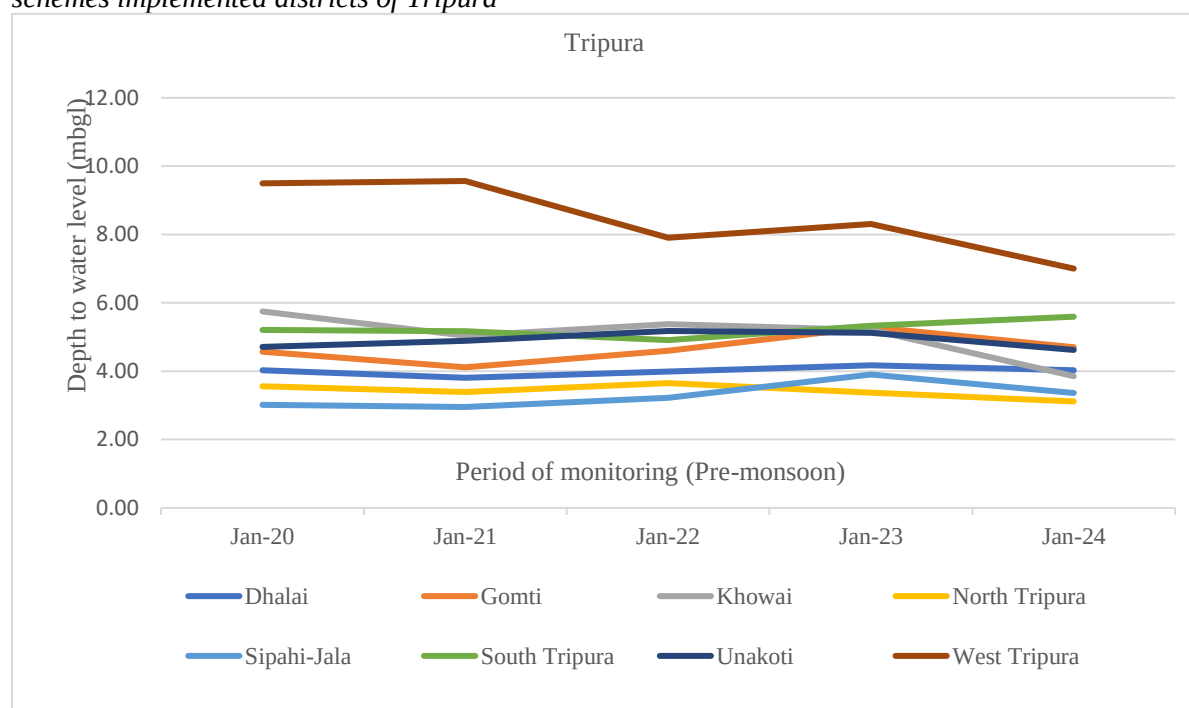


Table 5.b. Post -monsoon depth to water level trend for years 2020 to 2024 in PMKSY-HKGP-GW schemes implemented districts of Tripura

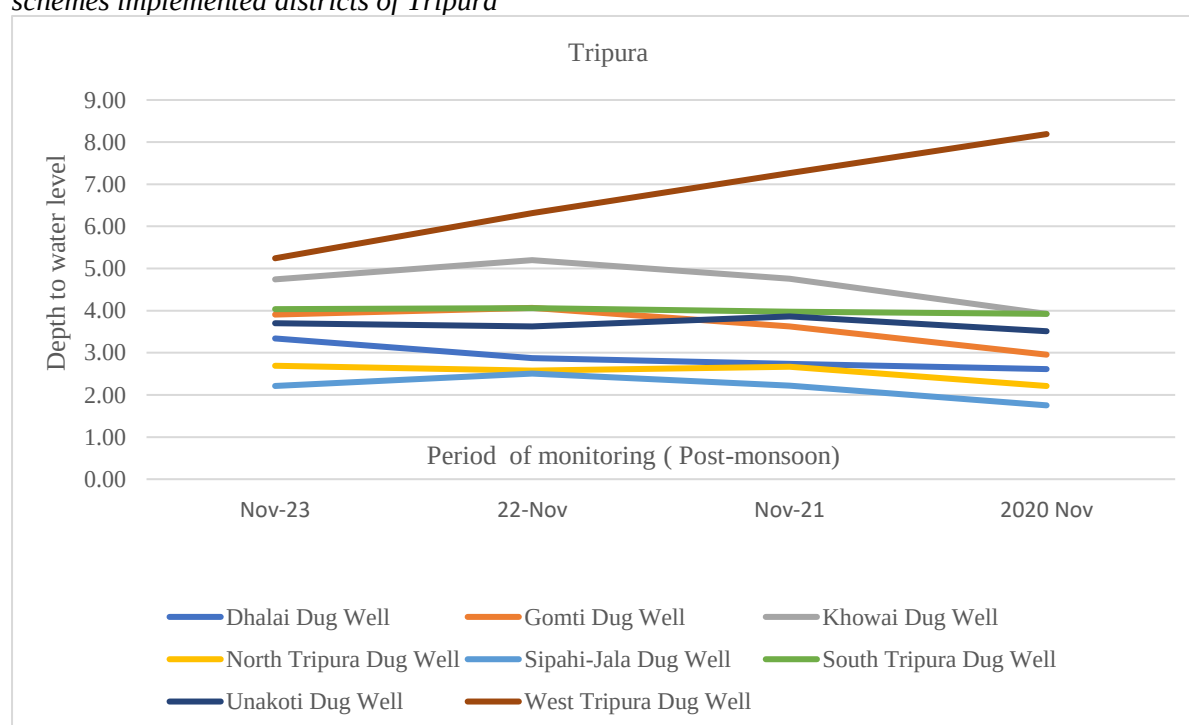


Table 6.a. Pre-monsoon depth to water level trend for years 2020 to 2024 in PMKSY-HKGP-GW schemes implemented districts of Nagaland

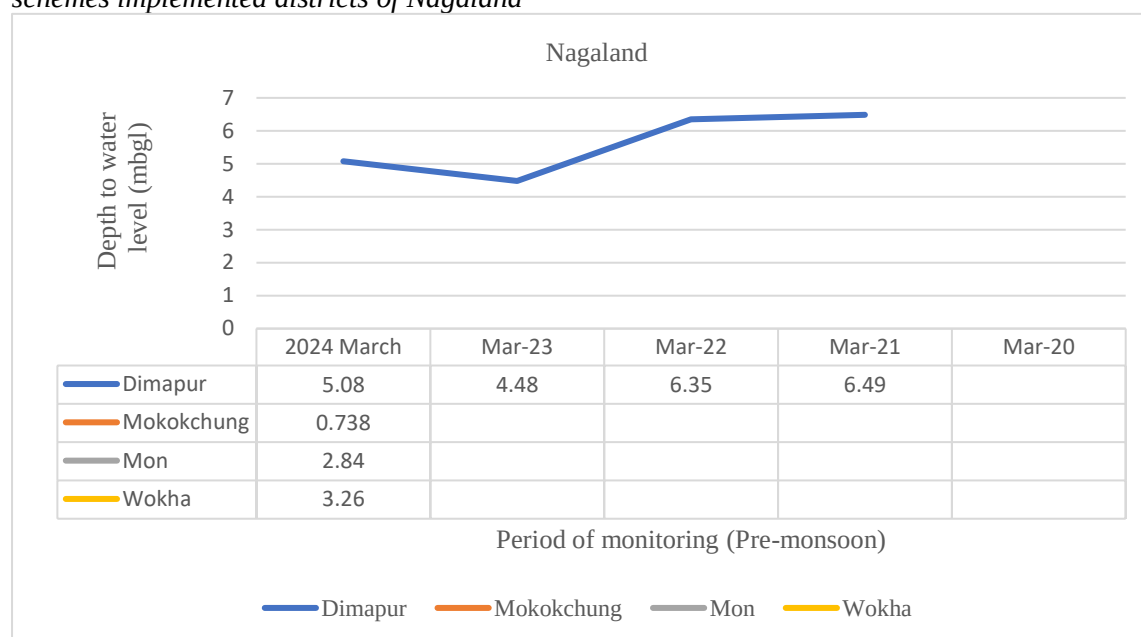
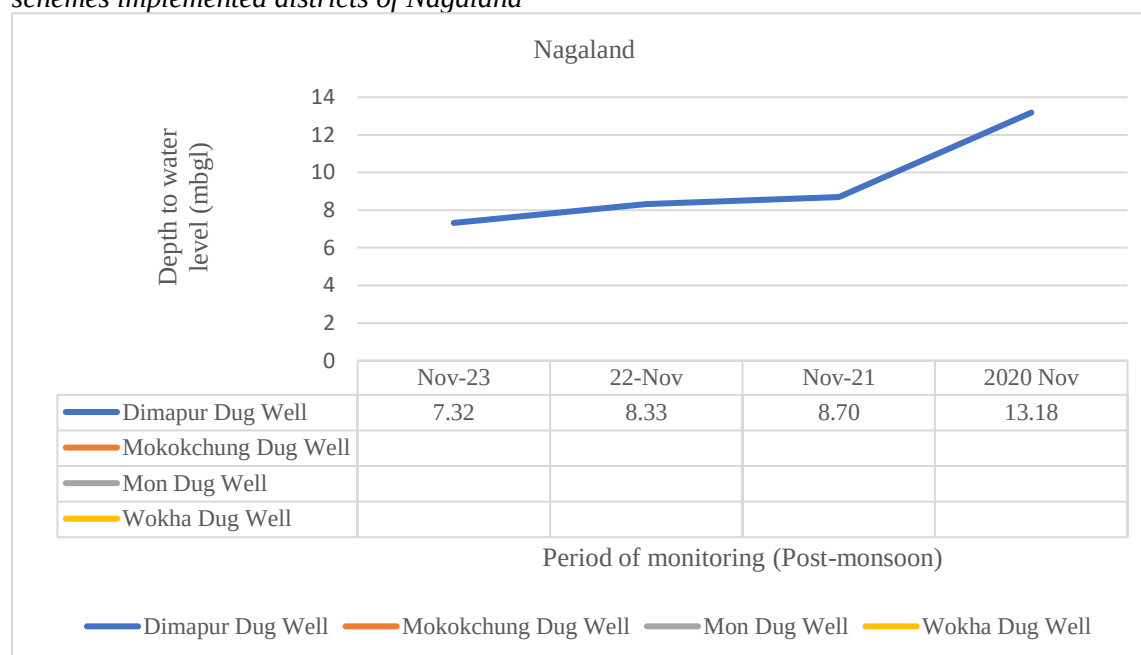


Table 6.b. Post-monsoon depth to water level trend for years 2020 to 2024 in PMKSY-HKGP-GW schemes implemented districts of Nagaland



Discussion

Impact Assessment of the Scheme

In overall this scheme has brought positive impact among the beneficiary farmers in the states of Assam, Arunachal Pradesh, Manipur, Mizoram, Nagaland, and Tripura. Since, the beneficiaries are equipped with assured irrigation water the beneficiaries could manage easily the uncertainties experienced with rainfed farming. Moreover, the guaranteed irrigation enhances the hope on the profitable agriculture to the farmers. It is also noted that some beneficiaries were engaged in poultry, dairy and fishery farming along with the cultivation of crops after implementing this scheme which would eventually improve the socio-economic status of farmers. Field inspections and analysis revealed that there has been a visible increase in productivity of Sali Paddy in the districts covered under the scheme. Winter Paddy has seen

an increase in area and productivity due to availability of assured irrigation through tube wells, dug wells etc. Farmers have begun to cultivate winter paddy like boro paddy with the availability of water during dry non-monsoon seasons.

In some areas, early Ahu paddy is also being taken up with the availability of irrigation. Vegetable cultivation was done in very limited scale during prior to implementation of the ground water irrigation schemes due to limited availability of water. Once the wells are installed, beneficiaries now have avenues for water for cultivating rabi crops. Vegetables are being cultivated in more areas and with the application of water, there is a visible increase in productivity as well.

Socio Economic Impact

With the effective utilization of irrigation potential created (IPC) by these shallow tube wells, dug wells etc. the small and marginal beneficiary farmers have been raising their farm productivity by increasing cropping intensity and ultimately raising household income to enable them live a better quality of life. This has resulted the beneficiaries to create a market for their crop besides attaining self-sufficiency in food and adding value to their nutritional products. Further, the solar energy system forming an integral part of the scheme advocate for the green and climate friendly viable technology inherited with lesser maintenance cost may also serve the multiple needs of the farmers besides creating an avenue to earn revenue for the farmers by selling the excess power to power company. Thus, solar powered tube well schemes shall be pivotal to cater to the continued demand of water for the farmers and shall promote sustainable agriculture development, contribute to gross domestic product (GDP), and combat the adverse effects of climate change.

Solar water pumps are transforming irrigation practices in agriculture and providing a cost-effective and eco-friendly alternative to traditional pumps. With the government's support and the increasing demand for sustainable agriculture practices, the future of solar water pumps looks bright. With the growing demand for environmentally friendly solutions, it is the perfect time to make the switch. As a result, a total of 5406 nos. wells (42%) out of the total 12829 wells have been successfully implemented through solar energization with 100% solar in Arunachal Pradesh followed by Mizoram with 88%, Nagaland 74.4%, Manipur 45.5 %, Assam 37%, and Tripura 17.66%.

Apart from uses in irrigating the land under agriculture, tube wells and dug wells are also being used for other allied non-agricultural activities. Rabi crops are being cultivated many areas in almost all districts covered by the schemes. Practice of winter paddy is also observed to be on an increasing as the availability of water has increased with the implementation of the scheme. There is a trend of adoption of double/multiple cropping as water is available during critical stages.

Thus, the scheme enabled the farmers to adopt multiple and mixed cropping in the command area, thereby creating a livelihood opportunity for the farmers by increasing their income and attaining self-sufficiency in production of consumable farm products like rice, vegetables, fruits, beans, and cereals due to access of ground water irrigation.

Impact on Ground Water level

The shallow tube wells, dug wells installed under the scheme, have been effectively delivering sufficient discharge to irrigate the crops in the command area. No significant decline of ground water level has been observed in most of the scheme sites and area due to withdrawal of groundwater under the scheme. This is due to the fact that states of north-eastern region of India have received plenty of rainfall with substantial annual recharge of the groundwater aquifer, thereby maintaining the ground water table in stable condition. Further, the annual recharges from the canals, rivers, check dams and other surface sources etc. also contribute significantly to ground water recharge. This is clearly substantiated by the report of GWRE, 2020,2022, 2023 and 2024 which suggest that the ground water scenario in NE states are falls under safe category.

Challenges and limitations

As regards challenges, the following points were generated from the field verification with beneficiary farmers –

- i. Low voltage, frequent power cuts and high electricity bills in case of electric pump sets.
- ii. In case of solar pump, beneficiaries have reported of low discharge after 2 pm during winter season and limited operation time.
- iii. Need of trainings to expertise proper servicing and maintenance of the solar and electrical pumps
- iv. Need of more micro-irrigation practices to farmers in order to enhance the crop command area and certainly influence in the constructive growth of the state economy.
- v. Need of extensive coverage beneficiaries in the groundwater potential areas so that all the eligible farmers may be benefited.
- vi. To motivate the community and make the people to own the scheme and to create an enabling environment for enhanced inclusion of community, more impetus may be given to awareness creation.
- vii. Based on the discussions with key stakeholders, it was suggested that the regular, robust monitoring may be taken up.
- viii. Reliance on rain-fed farming involves risk which can contribute to a reluctance to invest in agricultural inputs. It is suggested that the project may be extended to more beneficiaries for a larger boost to farmers' confidence.

Conclusion

There is no significant change/decline of groundwater level in most of the scheme sites and area due to withdrawal of groundwater for irrigation under this scheme. Considering the available ground water potential in the implementing states of NER, especially for Irrigation sector, there is scope for further extractions of ground water for irrigation purposes to meet the demand of small and marginal farmers. The irrigation water from shallow tube wells, dug wells etc. after having met the crop water requirements, undergo percolation with a little and negligible amount lost due to evapotranspiration. As considerable amount of rainfall is received in the region, sustainable development groundwater in those water logging areas may help in the management sector.

Acknowledgement

The author would like to express his heartfelt gratitude to the Chief Patron of INC-IAH and Chairman, Central Ground Water Board, Faridabad to publish the research paper. Author also extend sincere thanks to the Patron and Executive Editor of INC-IAH for giving the opportunity to publish the paper. Thanks also extend to scientists from CGWB, NER for giving valuable information and other technical inputs to prepare this research paper. Special thanks to Regional Director, CGWB, NER, Guwahati for providing facilities during the preparation of the paper. The author would like to acknowledge Department of Water Resource, River Development & Ganga rejuvenation, Ministry of Jal Shakti for the overall support and guidance during implementation of the PMKSY-HKGP-GW project and its data compilation. Thanks, are also extended to all state implementing agencies of PMKSY-HKGP-GW schemes for providing the data and necessary information of the respective states.

Reference

- Central Ground Water Board, Ministry of Water Resources, New Delhi (October 2017), Report of the Groundwater Resources Estimation Committee (GEC-2015) Methodology
- Central Ground Water Board (2019) National Compilation on Dynamic Ground Water Resources of India, 2017. Department of Water Resources, River Development & Ganga Rejuvenation, Ministry of Jal Shakti, Government of India.

Central Ground Water Board (2020) National Compilation on Dynamic Ground Water Resources of India, 2020. Department of Water Resources, River Development & Ganga Rejuvenation, Ministry of Jal Shakti, Government of India.

Central Ground Water Board, North Eastern Region, (2022) Ground Water Year Book, 2021-22, Department of Water Resources, River Development & Ganga Rejuvenation, Ministry of Jal Shakti, Government of India.

Central Ground Water Board (2022) National Compilation on Dynamic Ground Water Resources of India, 2022. Department of Water Resources, River Development & Ganga Rejuvenation, Ministry of Jal Shakti, Government of India.

Central Ground Water Board, North Eastern Region, (2023) Ground Water Year Book, 2022-23, Department of Water Resources, River Development & Ganga Rejuvenation, Ministry of Jal Shakti, Government of India.

Central Ground Water Board (2023) National Compilation on Dynamic Ground Water Resources of India, 2023. Department of Water Resources, RD & GR, Ministry of Jal Shakti, Government of India.

Central Ground Water Board, North Eastern Region, (2024) Ground Water Year Book, 2023-24, Department of Water Resources, River Development & Ganga Rejuvenation, Ministry of Jal Shakti, Government of India.

Central Ground Water Board (2024) National Compilation on Dynamic Ground Water Resources of India, 2024. Department of Water Resources, River Development & Ganga Rejuvenation, Ministry of Jal Shakti, Government of India.

Central Ground Water Board (PMKSY Section, NER, 2022), Physical and financial report of PMKSY-HKKP-GW schemes in respect of Arunachal Pradesh, Assam, Manipur, Mizoram, Nagaland, Tripura

Central Ground Water Board (PMKSY Section, NER, 2022), Compilation of 3rd Party Evaluation report of PMKSY-HKKP-GW schemes of Arunachal, Assam, Manipur, Mizoram, Nagaland, and Tripura Government of India, Ministry of Water Resources, River Development & Ganga Rejuvenation (Ground Water Section, 2019), Revised Operational Guideline of Groundwater irrigation Scheme under PMKSY-HKKP-GW vide OM.No. P-15011/24/2016-SPR/2037-2105 dated July 2018 and T-15013/1/2018-GW May 2019.

Central Ground Water Board, Ministry of Water Resources, River Development & Ganga Rejuvenation, Government of India, PMKSY-HKKP-GW Workshop at CSMRS, New Delhi dated 28th February 2019

MI Census (2023) Report of 6th Census of Minor Irrigation Schemes. Minor Irrigation (Statistics Wing), Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India.

Government of India (2012), National Water Policy, Ministry of Water Resources, Government of India



Delineation of Groundwater Recharge Potential Zones using Geospatial Techniques: A Comparative Analysis of Raster Calculator and Weighted AHP Tools

Suhani Srujanika¹, Prabhu Prasad Das², Bhavana Umrikar¹

1. Department of Geology, Savitribai Phule Pune University, Pune- 411007

2. Department of Geology, Dharani Dhar University, Keonjhar- 758001

E-mail: s.srujanika@gmail.com

Abstract

Replenishing groundwater is critical for managing both surface and subsurface water resources effectively. Particularly in coastal areas, where the intrusion of saltwater causes a reversal in the hydraulic gradient, the process of groundwater recharge becomes essential to uphold an increased flow of freshwater and sustain the elevated hydraulic gradient. Keeping this in view, the Groundwater Recharge Potential Zonation (GRPZ) map for parts of Jagatsinghpur district of Odisha, India, was generated through the application of the geospatial techniques. The GRPZ map for the study area was generated by integrating nine influencing layers using the raster calculator tool and the Weighted Overlay Analysis (WOA) method. Rainfall, Topographic Wetness Index (TWI) and Normalized Difference Vegetation Index (NDVI) are the most sensitive parameters followed by Land Use Land Cover (LULC), Geomorphology, Drainage Density, Slope, Lineament Density, and Elevation. The Analytical Hierarchy Process (AHP), involving pair-wise matrix analysis, was employed to compute the geometric mean and normalized weight for each parameter. Subsequently, the layers with normalized weights were overlaid mathematically to create a map delineating the potential zones for aquifer recharge. The study region has been categorized into four recharge potentials: very high (3.88%, 26.79 km²), high (40.26%, 278.06 km²), moderate (51.89%, 358.32 km²), and poor (3.97%, 27.42 km²). Further, the raster calculator was used to generate the GRPZ map through raster addition which depicts a considerable variation in the area under the four zones: very high (3.35%, 23.13 km²), high (26.64%, 183.98 km²), moderate (66.65%, 460.27 km²), and poor (3.36%, 23.21 km²). The GRPZ map obtained depicts a significant opportunity for implementing aquifer recharge programs and avoid the seawater intrusion.

Keywords: Coastal aquifers, Odisha, recharge zones, GIS-AHP

Introduction

Groundwater replenishment is a critical component of water resource management, especially in regions where both surface and subsurface water resources play vital roles in meeting the demands of agriculture, industry, and domestic use. Groundwater, which serves as a crucial source of fresh water for many communities, is increasingly under stress due to over-extraction and contamination. In coastal regions, the issue is compounded by saltwater intrusion, which can reverse the natural hydraulic gradient and degrade water quality (Custodio, 2010). Ensuring effective groundwater recharge is thus essential to maintain a sustainable supply of freshwater and to counteract the adverse effects of saltwater intrusion.

Geospatial techniques have proven to be invaluable tools in assessing groundwater recharge potential, as they allow for the integration and analysis of multiple environmental parameters (Elbeih, 2015). These techniques facilitate the creation of detailed maps that highlight areas with varying potential for groundwater recharge, providing essential data for informed water management decisions. Several

researchers (Murmu et al., 2019; Arulbalaji et al., 2019) have utilized the integration of remote sensing and GIS to identify groundwater prospect zones.

By employing advanced geospatial methods, a Groundwater Recharge Potential Zonation (GRPZ) map was developed to identify areas most suitable for groundwater recharge. Several factors influence groundwater fluctuations, including geomorphology, lithology, topography, slope, soil, precipitation, drainage patterns, land use/land cover (LULC), and hydrological conditions (Murmu et al., 2019). The analysis incorporated nine key parameters: Rainfall, Topographic Wetness Index (TWI), Normalized Difference Vegetation Index (NDVI), Land Use Land Cover (LULC), Geomorphology, Drainage Density, Slope, Lineament Density, and Elevation (Naghbi et al., 2015). Using the Analytical Hierarchy Process (AHP), each parameter was assigned a weight based on its relative importance, ensuring a robust and comprehensive assessment (Saaty, 1980). The method is straightforward, efficient, transparent, and reliable for conducting multi-criteria analysis (Dar et al., 2020). The raster calculator is another tool that allows to perform calculations based on the existing pixel values of the input raster layers. This tool can also be used to create a GRPZ map by carrying out the summation of the raster layers of the aforementioned parameters based on their rankings, without considering their weights in the hierarchy.

The GRPZ map categorizes the study area into four distinct zones of recharge potential: very high, high, moderate, and poor. This classification provides a strategic framework for targeted groundwater recharge initiatives, highlighting the areas where interventions can be most effective in enhancing recharge and preventing seawater intrusion. The insights gained from the GRPZ map are crucial for policymakers and water resource managers aiming to develop sustainable groundwater management practices.

Study area

The Jagatsinghpur district in Odisha, India, presents a significant case study for the application of geospatial techniques in groundwater management. The present study aims to understand the potentiality of the coastal blocks of Jagatsinghpur district namely Balikuda and Ersama for groundwater recharge. The longitudinal extent of the study area is from 86°12' E to 86°40' E and the latitudinal extent is from 19°56' N to 20°18' N (Fig. 1). The areal extent of the region is 690.59 km². The average annual rainfall measured for the years 2017 - 2021 is 2101.5 mm. The area is prone to cyclonic rainfalls during the pre- and post-monsoon seasons.

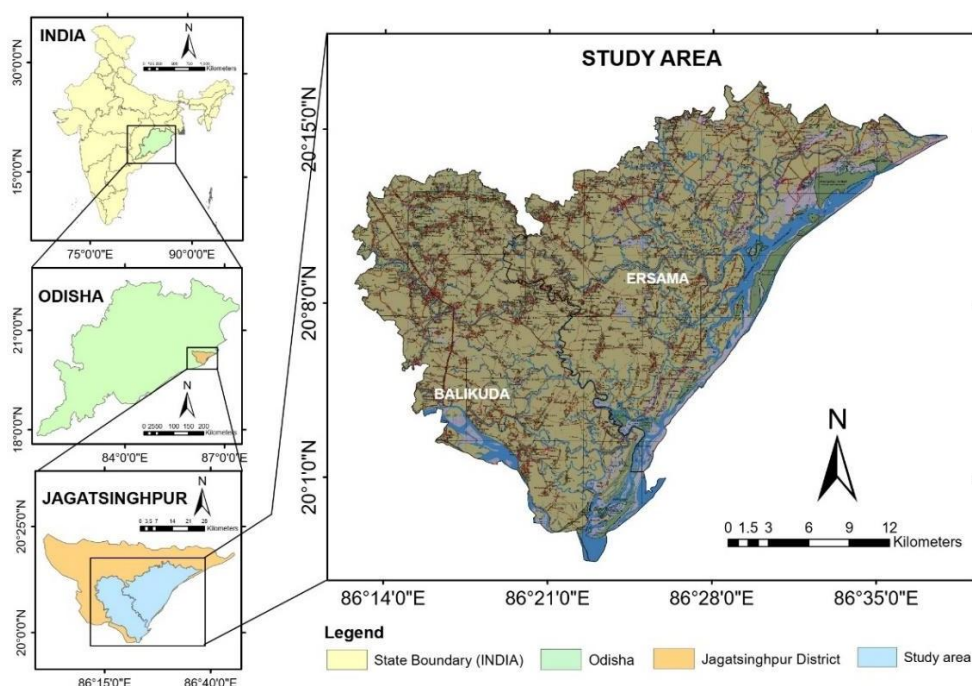


Fig. 1: Political and topographic setting of the study area

The district spreads over alluvial deposits of river Mahanadi and its distributaries that resulted into fertile agricultural land. Thus, agriculture and aquaculture are the main source of income in this region. The study area is bounded by the Devi river in the south. The Devi river, one of the distributaries of the Mahanadi river, falls into the Mahanadi basin and is rich in biodiversity including dense mangroves, migratory birds, olive ridley turtles and red crabs. One of the major ports of India, the Paradeep port lies in close proximity towards the north of the study area in the Kujang block. This region faces challenges due to its coastal location making it vulnerable to frequent cyclones, coastal flooding, water logging and specifically seawater intrusion. Intensive use of groundwater for drinking, household uses, irrigation and industrial purposes has resulted in groundwater exploitation.

Materials and Methods

Preparation of thematic maps

To delineate groundwater potential zones, a base map and nine thematic layers—Rainfall, TWI, NDVI, LULC, Geomorphology, Drainage Density, Slope, Lineament Density, and Elevation—were generated using conventional data and remote sensing tools in ArcGIS software. Survey of India (SOI) toposheets (E45C5, F45U4, F45U7, F45U8, F45U11, F45U12) were georeferenced, and the clip and mosaic tools were utilized to create the base map for the two blocks. Digital Elevation Model (DEM) data with a 25m resolution was obtained from the Bhuvan geoportal of NRSC/ISRO (<https://bhuvan.nrsc.gov.in/home/index.php>) to prepare the elevation map. The slope map was derived from the DEM data using the surface spatial analyst tool. The drainage map was manually digitized from toposheets and Google Earth Pro satellite imagery, and the drainage density map was created using the line density tool.

The TWI map offers insights into the spatial patterns of wetness and upslope contributing areas, and it is widely used to quantify topographic control on hydrological processes. The TWI is defined as-

$$TWI = \ln \frac{a}{\tan b}$$

where, a is the local upslope area draining through a certain point per unit contour length and $\tan b$ is the local slope in radians. The Topographic Wetness Index (TWI) map was created from the slope map using ArcGIS software's spatial analyst and raster calculator tools. This process involved calculating flow direction, flow accumulation, the tangent of the slope, and ultimately the TWI using straightforward equations (Beven & Kirkby, 1979).

The geomorphology and lineament data were obtained from the Bhukosh website, managed by the Geological Survey of India (GSI). After clipping this data to fit the study area's extent, it was converted into raster format for further analysis. The lineament density map was then produced using the line density tool, with the lineament map as the input.

For the land use/land cover map, Sentinel-2 data provided by ESRI, with a resolution of 10 meters, was utilized. The Normalized Difference Vegetation Index (NDVI) map was generated from the Near Infrared (NIR) band (band 5) and the red band (band 4) of the Landsat 8 imagery, which has a resolution of 30 meters. This was achieved using the specified formula in the raster calculator tool.

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

Rainfall data for the years 2017 to 2021 was obtained from the PERSIANN-Cloud Classification System (PERSIANN-CCS), a product developed by the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine (UCI) (Sorooshian et al., 2000). This system provides global precipitation data at a resolution of 4 km x 4 km (0.04° x 0.04°). The data was processed using the raster calculator tool to compute the average annual rainfall. To refine the data,

the Inverse Distance Weighting (IDW) interpolation tool was applied, resulting in the final average annual rainfall map (Watson & Philip, 1985).

All thematic maps were projected using the UTM Zone 45 coordinate system and converted into raster format with a pixel size of 30m x 30m. The methodology is illustrated in a flowchart presented in Fig. 2.

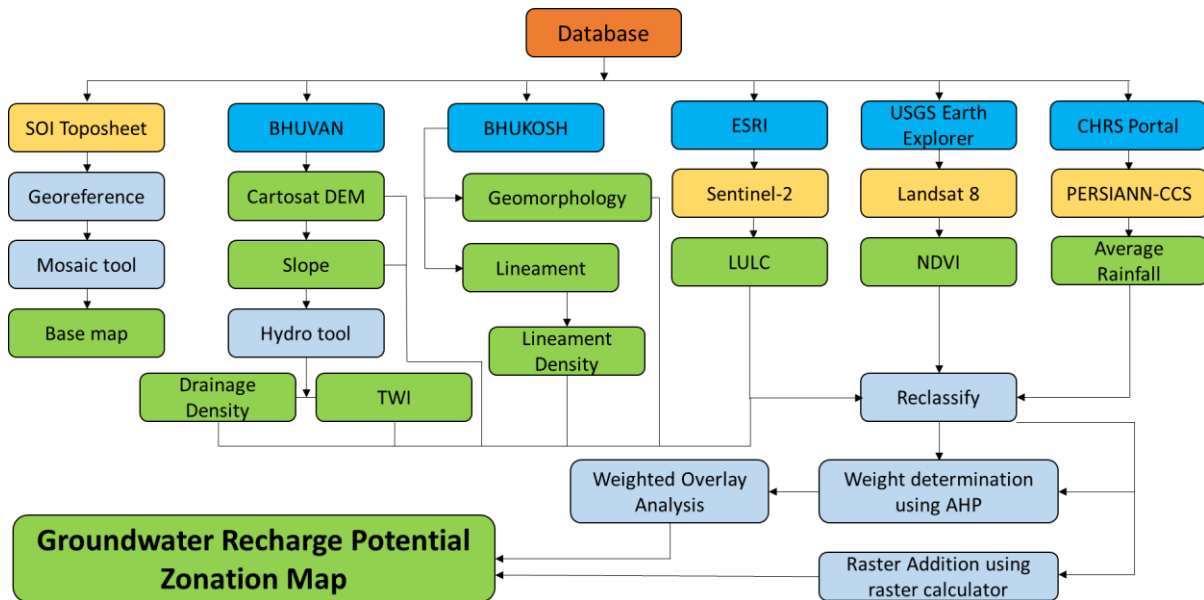


Fig. 2: Methodology flowchart for the study

Reclassification of thematic layers and ranking

Before performing overlay analysis, reclassification is essential to ensure that the classes of each influencing factor are accurately identified and utilized during the overlay process. Each class is assigned a rank to indicate its relative importance within the influencing factor. The ranks are based on the relationship between each factor and the groundwater recharge and movement at a given location. This reclassification step prepares the layers for weighted overlay analysis and raster addition within the GIS platform. The rankings of the reclassified layers are presented in Table 2.

Assigning weightages and weight normalization using Analytical Heirarchy Process (AHP)

The Analytical Hierarchy Process (AHP) is a pairwise comparison analytical method developed by Saaty (1980, 1990). It is utilized to compute normalized weights and the geometric mean of individual parameters, generating relative ratio scales from paired comparisons (Murmu et al., 2019). AHP is a leading method in groundwater prediction modeling, known for providing precise, rapid, and cost-effective results (Murmu et al., 2019). One notable advantage of the AHP technique is its focus on the judgment of each individual property, which aids in making robust decisions (Saaty, 1980). In integrated analysis, assigning appropriate weights to each class is crucial, as the accuracy of the output relies on these weights. Table 1 shows the pairwise comparison matrix generated from ranking of each of the influencing factors. Further, to normalize the matrix, each entry in the column is divided by the column sum.

Consistency Analysis

To compute the consistency vector, the values from the pairwise comparison matrix were multiplied with the normalized pairwise matrix values of the thematic layers using the matrix multiplication

function. The Consistency Index (CI), which measures the degree of consistency, was calculated using the following formula:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Where, λ_{max} represents Consistency Vector and n represents number of parameters used.

The Consistency Ratio (CR) is calculated from Consistency Index and Random Index (RI) using the formula:

$$CR = CI/RI$$

Where, RI is the Randomized Index. The RI value indicates the randomness standard deviation, applicable to matrices of different sizes and variables (Saaty, 1980).

The CR value of 0.1 or less is acceptable. A value greater than this will require the judgements to be reconsidered. For the given study, the consistency ratio was calculated to be 0.056 (Table 1).

Table 1: Pairwise comparison matrix for nine influencing layers developed for groundwater recharge potential zoning using AHP

Parameter	Geomorphology	DEM	Drainage Density	Lineament Density	Slope	Rainfall	TWI	NDVI	LULC	Criteria weight	Influence (%)
Geomorphology	1	2	2	3	1	0.25	0.33	0.33	2	0.103	10
Elevation	0.5	1	0.5	0.33	0.5	0.33	0.33	0.33	0.5	0.045	5
Drainage Density	0.5	2	1	2	1	0.33	2	0.5	0.33	0.093	9
Lineament Density	0.33	3	0.5	1	2	0.33	0.5	0.5	0.33	0.074	7
Slope	1	2	1	2	1	0.2	0.5	0.33	1	0.079	8
Rainfall	2	3	3	3	1	1	2	3	1	0.195	20
TWI	2	3	0.5	2	2	0.5	1	2	2	0.148	15
NDVI	2	3	2	2	3	0.33	0.5	1	2	0.145	14
LULC	0.5	2	3	3	1	1	0.5	0.5	1	0.119	12
Consistency Index											0.082
Random Index											1.46
Consistency Ratio											0.056

Weighted Overlay Analysis (WOA)

The Weighted Overlay tool is a widely used method for overlay analysis in addressing multicriteria problems, such as site selection and suitability modeling. This tool superimposes newly categorized raster layers with the desired characteristics. A rating scale is employed to assign a value to the grid cells of each evaluated input thematic layer. The process begins by reclassifying the values in the input raster into a unified evaluation scale that represents suitability, preference, risk, or a similar measure. Next, the cell values of each input raster are multiplied by the raster's assigned weight of importance. Finally, the resulting cell values are summed to generate the output raster. This method allows for a comprehensive assessment by integrating various factors into a single analytical framework (Malczewski, 1999; Eastman, 1999).

Raster Calculator

Generating a groundwater potential zonation map using raster addition involves combining multiple thematic layers, each depicting various factors that affect groundwater recharge. Initially, each layer is reclassified into a standardized scale to represent its suitability or influence on groundwater potential.

These standardized layers are then merged through raster addition in ArcGIS software, which sums the absolute cell values of each layer without applying specific weights to them. This approach allows for the straightforward integration of diverse factors to identify zones with varying groundwater recharge potential (Burrough & McDonnell, 1998).

Table 2: List of reclassified thematic layers along with the class rankings and criteria weightages.

Parameters	Classes	Ranking	Criteria weight	Influence (%)
Geomorphology	Swamp/Beach Ridge-Swale Complex/Estuarine Island/Spit/Barrier Bar/Mangrove swamp/Channel Island	1	0.103	10
	Older Coastal Plain/Cut-off Meander/Older Deltaic Plain	2		
	Aggraded palaeochannel/Natural Levee/Beach Ridge/Younger Coastal Plain/Tidal Flat/Beach/Younger Deltaic Plain	3		
	Water Bodies - Pond/River/Creek Network/Braid Bar/Channel Bar	4		
Elevation (m)	0 - 3	1	0.045	5
	3 - 8	2		
	8 - 13	3		
	13 - 40	4		
Drainage Density (km/km ²)	0 - 2	1	0.093	9
	2 - 6	2		
	6 - 11	3		
	11 - 19	4		
Lineament Density (km/km ²)	0 - 0.124	1	0.074	7
	0.124 - 0.360	2		
	0.360 - 0.660	3		
	0.660 - 1.273	4		
Slope (degree)	5.360 - 25.310	1	0.079	8
	2.680 - 5.360	2		
	1.191 - 2.680	3		
	0 - 1.191	4		
Rainfall (mm)	1999.07 - 2050.28	1	0.195	20
	2050.28 - 2101.49	2		
	2101.49 - 2152.70	3		
	2152.70 - 2203.92	4		
TWI	4.483 - 8.430	1	0.148	15
	8.430 - 10.854	2		
	10.854 - 13.971	3		
	13.971 - 22.144	4		
NDVI	0.058 - 0.147	1	0.145	14
	0.147 - 0.221	2		
	0.221 - 0.452	3		
	-0.119 - 0.058	4		
LULC	Built Area	1	0.119	12
	Bare ground/Range land	2		
	Trees/Agriculture	3		
	Water/Flooded vegetation	4		

Results and Discussion

The nine layers influencing the potential of groundwater recharge in the study area are Rainfall, TWI, NDVI, LULC, Geomorphology, Drainage Density, Slope, Lineament Density, and Elevation in decreasing order of their weightages.

Rainfall

Rainfall is a key factor in recharging groundwater, as it facilitates the infiltration of surface water, which replenishes groundwater reserves. For a span of 5 years from 2017 to 2021, the maximum average annual rainfall was recorded to be 2204 mm and the minimum was 1999 mm (Fig.3a). Within the hierarchy framework, rainfall was given the highest priority.

Topographic wetness Index (TWI)

TWI is a unitless parameter commonly utilized to quantify the influence of topography on hydrological processes. It represents the ratio between the upslope area draining through a certain point per unit contour length in an area to the local slope in radians. It directly correlates to the freshwater flow in the region which makes it an important parameter. The TWI for the part of the Mahanadi delta ranges from 4.483 to 22.144 (Fig. 3b).

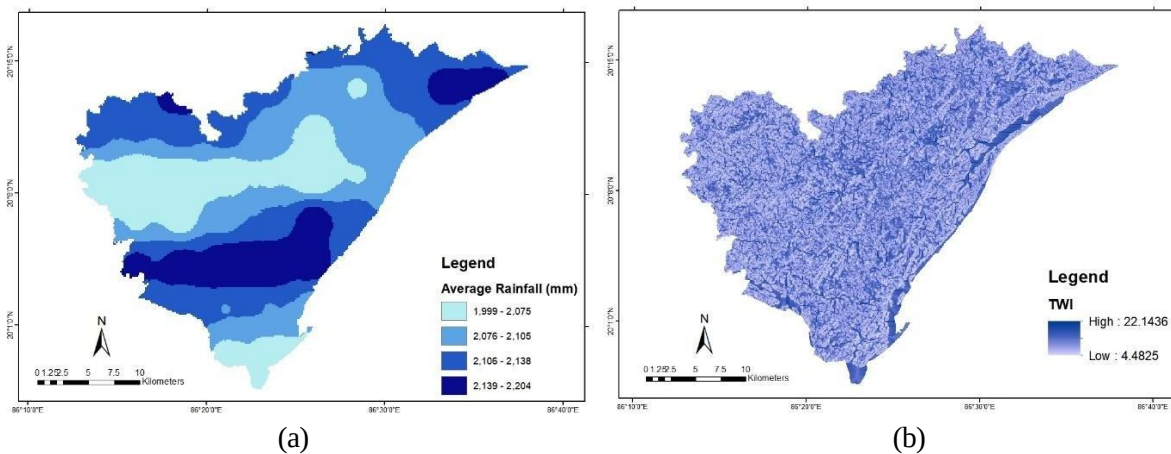


Fig. 3: (a) Average annual rainfall map; (b) Topographic Wetness Index map

Normalized Difference Vegetation Index (NDVI)

NDVI plays a significant role in influencing groundwater recharge by reflecting vegetation health and density, which are closely associated with soil moisture and evapotranspiration rates. In the region, the NDVI values range from -0.119 to 0.452 (Fig. 4a). Areas with healthy vegetation, as indicated by high NDVI values, typically have higher soil moisture content and are more conducive to water infiltration, thus enhancing groundwater recharge. In contrast, areas with low NDVI values tend to have reduced vegetation cover, leading to increased surface runoff and decreased groundwater recharge (Pettorelli et al., 2014). It is evident from the map (Fig. 4a) that the western part of the study area are covered by dense vegetation. Consequently, NDVI is an essential parameter for evaluating and mapping groundwater recharge potential.

Land Use Land Cover (LULC)

LULC significantly influence groundwater recharge by altering surface runoff, infiltration rates, and evapotranspiration (Scanlon et al., 2002). Areas with natural vegetation and permeable soil, such as forests and agricultural lands, typically enhance groundwater recharge due to higher infiltration and reduced surface runoff. Conversely, urban areas and barren lands, characterized by impermeable

surfaces and altered soil properties, often impede water infiltration, leading to increased runoff and reduced groundwater recharge. The study area is dominated by agriculture and aquaculture practices (CGWB, 2019). This is evident from the extended part of the creek inland (Fig. 4b).

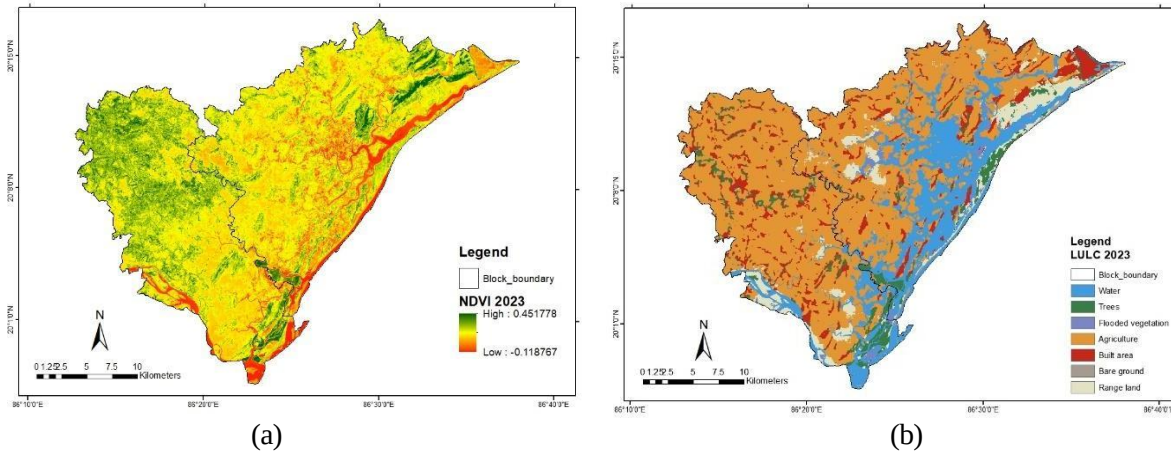


Fig. 4: (a) Normalized Difference Vegetation Index map; (b) Land Use Land Cover map

Geomorphology

Geomorphology is a key factor in understanding landform evolution and its influence on groundwater potential, as it regulates the subsurface movement of groundwater (Murmu et al., 2019; Thapa et al., 2017). Features such as dunes, estuaries, and coastal plains significantly affect water infiltration and storage. Sandy and porous geomorphic formations, such as dunes, generally promote higher groundwater recharge rates due to their permeability, which allows more water to seep into the ground. In contrast, clayey and rocky formations hinder infiltration, thus reducing recharge rates. Furthermore, coastal geomorphology can influence seawater intrusion into freshwater aquifers, impacting the quality and quantity of groundwater (Cooper & Pilkey, 2004; Werner & Simmons, 2009). The region's geomorphology includes typical coastal features such as paleochannels, barrier bars, beach ridges, channel islands, swamps, and tidal flats (Naik, 2018) (Fig. 5a).

Drainage Density

Drainage density plays a significant role in influencing hydrogeological characteristics by governing the underlying lithology. It quantifies the proximity of stream channels within a given area (Murmu et al., 2019). This parameter is determined by calculating the total length of stream channels per unit area. The drainage density ranges from 0 to 18.71 km/km² (Fig. 5b).

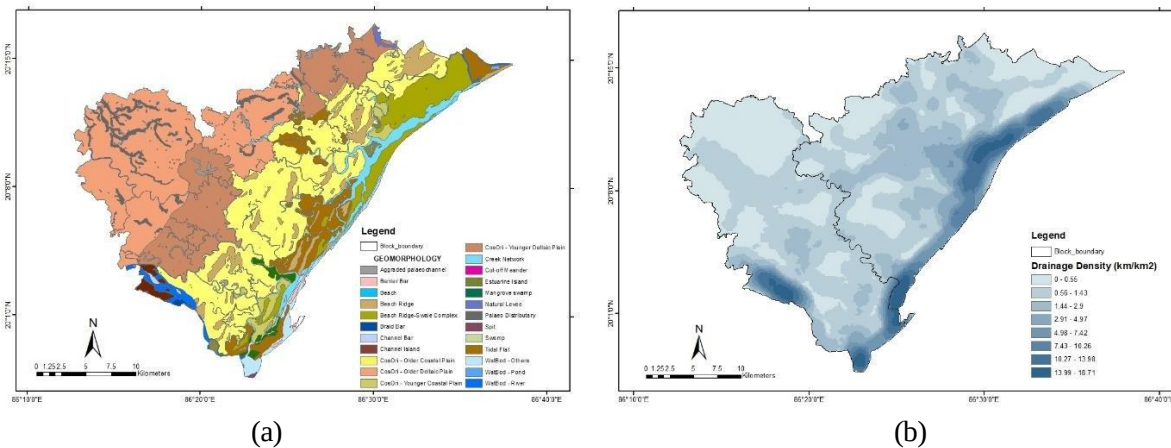


Fig. 5: (a) Geomorphology map; (b) Drainage Density map

Slope

The slope of the land surface exerts a notable influence on groundwater recharge by directly impacting water runoff and infiltration rates. The slope ranges from a minimum of 0° to a maximum of 25.31° (Fig. 6a). Steeper slopes tend to accelerate surface runoff, diminishing the volume of water that can percolate into the soil and thereby decreasing groundwater recharge rates. Conversely, gentler slopes facilitate slower runoff, enabling more water to seep into the ground and effectively recharge groundwater aquifers. Thus, slope characteristics play a critical role in determining the capacity of an area to replenish groundwater.

Lineament Density

Lineament density plays a crucial role in influencing groundwater recharge by identifying areas with increased concentrations of fractures and faults beneath the surface. These geological features serve as preferential pathways for water infiltration, enhancing connectivity between surface water and groundwater systems. Higher lineament density often correlates with greater groundwater recharge rates. The lineament density varies from 0 to 1.273 km/km^2 (Fig. 6b). For instance, the study area is characterized by three prominent faults oriented NE-SW, which divide the region into alternating uplift and depression zones. These zones include the Konark uplift, Puri depression, Nimapara- Balikuda uplift, and Paradeep depression as one moves northward (Das et al., 2020).

Elevation

Elevation impacts groundwater recharge by influencing the distribution and movement of surface water and precipitation. In areas with steep gradients and high elevations, rapid surface runoff is common, which can reduce the amount of water that infiltrates the ground. Conversely, lower elevation areas typically experience slower runoff and greater water accumulation, which enhances infiltration and recharge. In deltaic regions, such as the study area, elevation variation is minimal, leading to different recharge dynamics compared to more varied topographies. The elevation increases from 0 m to 40 m away from the coastline (Fig. 6c).

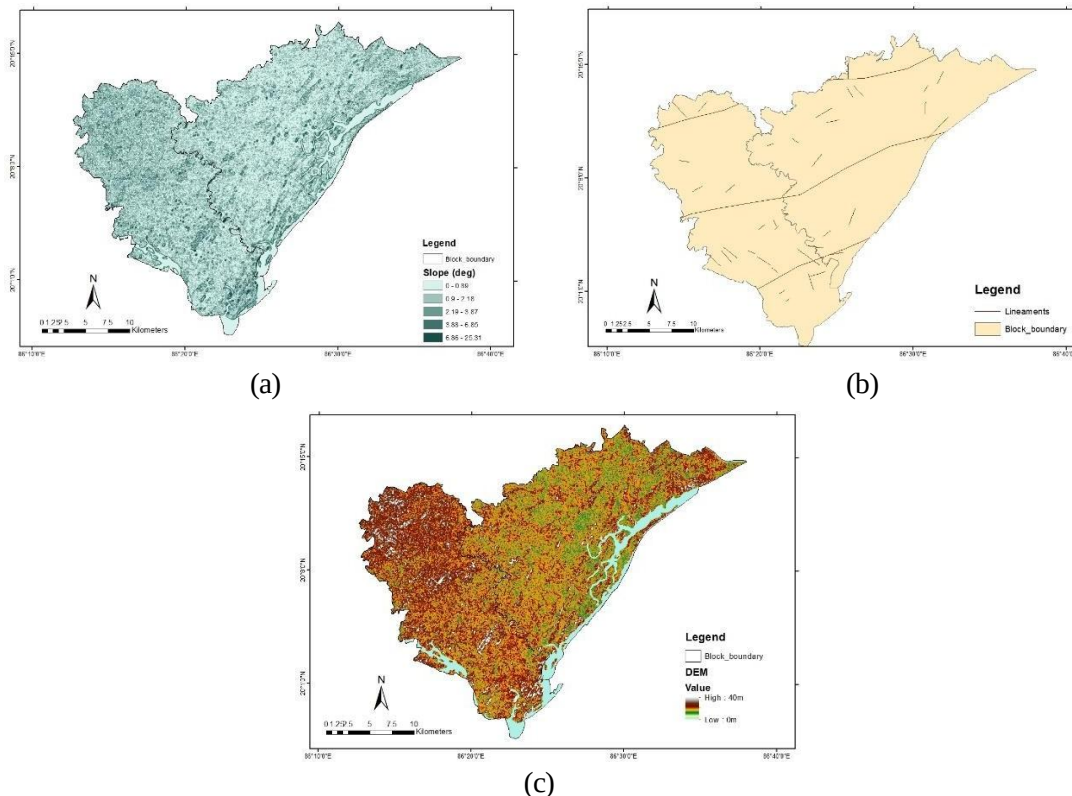


Fig. 6: (a) Slope map; (b) Lineament Density map; (c) Elevation map

Groundwater Recharge Potential Zones

The GRPZ map for the study area was generated by integrating nine influencing layers using the raster calculator tool and the Weighted Overlay AHP method. The study categorized four different classes of groundwater potential zones (GRPZs) on a scale of 1-4: poor, moderate, high, and very high. Using simple raster addition, the distribution of these zones was as follows: 'poor' areas covered 23.21 km² (3.36%), 'moderate' areas covered 460.27 km² (66.65%), 'high' areas covered 183.98 km² (26.64%), and 'very high' areas covered 23.13 km² (3.35%) (Fig. 7). However, when the Weighted Overlay AHP technique was applied, the distribution showed significant variation: 'poor' zones covered 27.42 km² (3.97%), 'moderate' zones covered 358.32 km² (51.89%), 'high' zones covered 278.06 km² (40.26%), and 'very high' zones covered 26.79 km² (3.88%) (Fig. 8). This variation likely resulted from the unassigned weightages in the raster calculator, highlighting the effectiveness of the Weighted Overlay AHP technique.

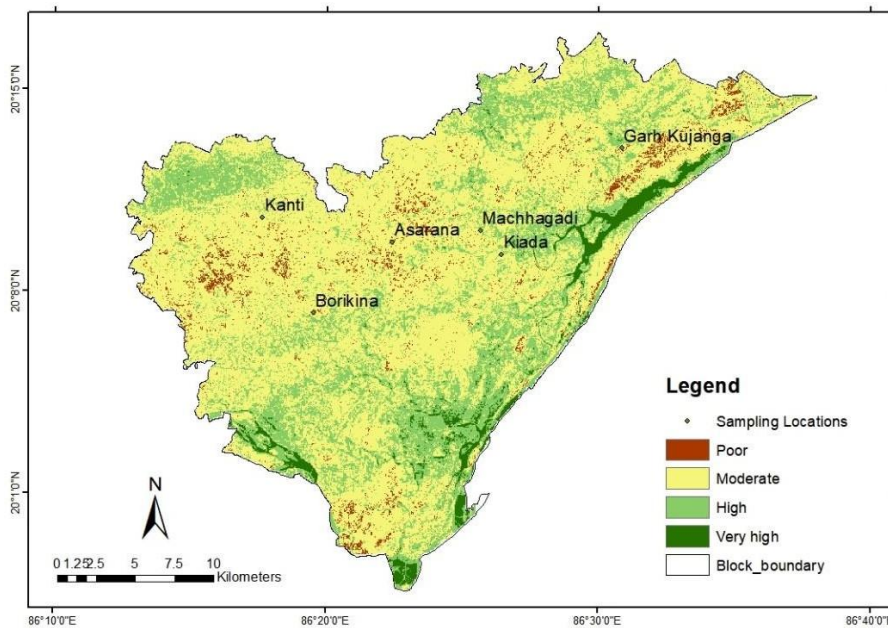


Fig. 7: Groundwater potential zonation map generated through raster addition technique

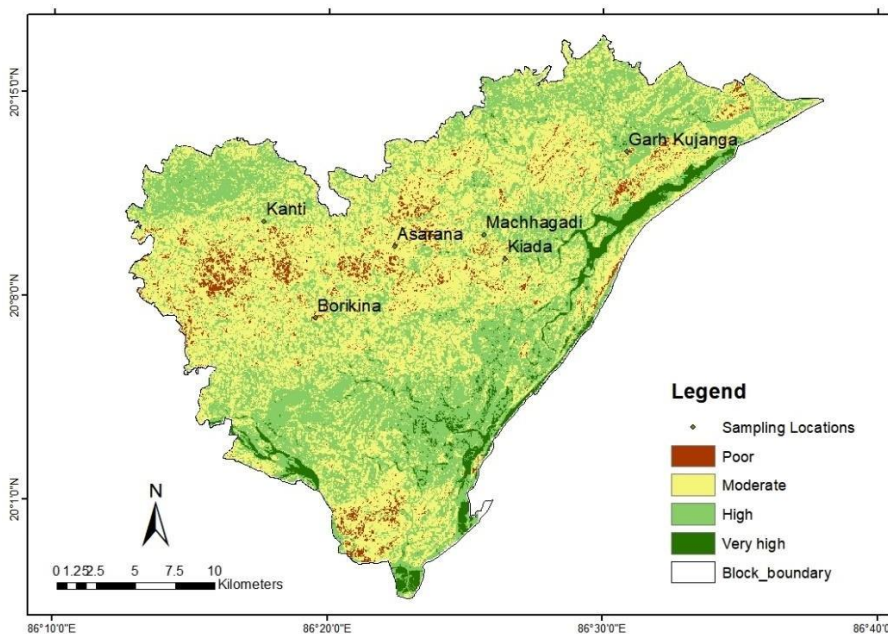


Fig. 8: Groundwater potential zonation map generated through weighted overlay AHP technique

Groundwater sample analysis for Total Dissolved Solids (TDS) revealed that certain villages, including Asarana, Borikina, Garh Kujanga, Kanti, Kiada, and Machhagadi, situated in the poor potential zone, exhibited high TDS levels exceeding 1000 mg/L, rendering the water unfit for drinking. Therefore, identifying and understanding groundwater recharge potential zones is crucial. This knowledge can enhance freshwater flux and prevent the reversal of the hydraulic gradient, ensuring a sustainable supply of potable water.

Conclusion

This study focused on the coastal blocks of Balikuda and Ersama in Jagatsinghpur district, Odisha, India, to evaluate the effectiveness of geospatial techniques and the Analytical Hierarchy Process (AHP) in identifying groundwater recharge potential zones. The study incorporated various thematic layers, including average rainfall, DEM, slope, geomorphology, LULC, NDVI, TWI, lineament density, and drainage density, to create the Groundwater Recharge Potential Zonation Map. The identification of high recharge potential zones is crucial for mitigating the intrusion of saline water into coastal aquifers. This detailed mapping can support measures such as Managed Aquifer Recharge, injection wells, artificial recharge basins, rainwater harvesting, permeable reactive barriers, and techniques for excluding saline water.

References:

- Arulbalaji, P., Padmalal, D. & Sreelash, K. (2019). GIS and AHP techniques based delineation of groundwater potential zones: a case study from Southern Western Ghats, India. *Scientific Reports*, 9(1), 2082.
- Beven, K. J. & Kirkby, M. J. (1979). A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Journal*, 24(1), 43-69.
- Burrough, P. A. & McDonnell, R. A. (1998). *Principles of Geographical Information Systems*. Oxford University Press.
- Cooper, J. A. G. & Pilkey, O. H. (2004). Sea-level rise and shoreline retreat: time to abandon the Bruun Rule. *Global and Planetary Change*, 43(3-4), 157-171.
- Custodio, E. (2010). Coastal aquifers of Europe: an overview. *Hydrogeology Journal*, 18(1), 269- 280.
- Dar, T., Rai, N. & Bhat, A. (2020). Delineation of potential groundwater recharge zones using analytical hierarchy process (AHP), *Geology, Ecology, and Landscapes*, pp. 1-16.
- Das, P. (2019) Hydrogeological framework, ground water development & aquifer management plan of Jagatsinghpur district, Odisha state, Central Ground Water Board, South Eastern Region, Bhubaneswar.
- Das, P., Sahoo, H. & Mohapatra, P. (2020). Assessing the effects of regional tectonic activity on groundwater flow in a coastal aquifer in India. *Environmental Earth Sciences*. 75. 1331. 10.1007/s12665-016-6161-9.
- Eastman, J. R. (1999). Multi-criteria evaluation and GIS. In *Geographical Information Systems* (Vol. 1, pp. 493-502).
- Elbeih, S. F. (2015). An overview of integrated remote sensing and GIS for groundwater mapping in Egypt. *Ain Shams Engineering Journal*, 6(1), 1-15.
- Malczewski, J. (1999). *GIS and Multicriteria Decision Analysis*. John Wiley & Sons.
- Murmu, P., Kumar, M., Lal, D., Sonker, I. and Singh, S. K. (2019). Delineation of groundwater potential zones using geospatial techniques and analytical hierarchy process in Dumka district, Jharkhand, India, *Groundwater for Sustainable Development*, Vol. 9, p. 100239.
- Naghbi, S. A., Pourghasemi, H. R. & Dixon, B. (2015). GIS-based groundwater potential mapping using boosted regression tree, classification and regression tree, and random forest machine learning models in Iran. *Environmental Monitoring and Assessment*, 188(1), 44.
- Naik, P. C. (2018) *Seawater Intrusion in the Coastal Alluvial Aquifers of the Mahanadi Delta*. Springer Briefs in Water Science and Technology. 2018. 978-3-319-66511-5.

- Nithya, T. S., Vijay Prabhu, M. & Nagarajan, R. (2019). Identification of groundwater recharge zones using remote sensing and GIS in Amaravathi basin. *Journal of Environmental Management*, 232, 236-248.
- Pettorelli, N., Laurance, W. F., O'Brien, T. G., Wegmann, M., Nagendra, H. & Turner, W. (2014). Satellite remote sensing for applied ecologists: opportunities and challenges. *Journal of Applied Ecology*, 51(4), 839-848.
- Saaty, T. L. (1980). *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. McGraw-Hill.
- Saaty, T. L. (1990). *Multicriteria Decision Making: The Analytical Hierarchy Process: Planning, Priority Setting, Resource Allocation*. RWS Publications.
- Scanlon, B. R., Healy, R. W., & Cook, P. G. (2002). Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal*, 10(1), 18-39.
- Sorooshian, S., Hsu, K., Gao, X., Gupta, H. V., Imam, B. & Braithwaite, D. (2000). Evaluation of PERSIANN system satellite-based estimates of tropical rainfall. *Bulletin of the American Meteorological Society*, 81(9), 2035-2046.
- Watson, D. & Philip, G. (1985). A refinement of inverse distance weighted interpolation. *Geoprocessing*, 2, 315-327.
- Werner, A. D. & Simmons, C. T. (2009). Impact of sea-level rise on sea water intrusion in coastal aquifers. *Ground Water*, 47(2), 197-204.



Assessing Drought Vulnerability in parts of Nira River Basin, Western India, using GIS and AHP Methods

Payal V. Waindeshkar¹, Bhavana Umrikar¹, Saikat Sengupta²

1. Department of Geology, Savitribai Phule Pune University, Pune- 411007
2. Department of Paleoclimate, Indian Institute of Tropical Meteorology, 411008
E-mail: payalwaindeshkar123@gmail.com

Abstract

Integrating geospatial tools with the Analytic Hierarchy Process (AHP) effectively assesses drought vulnerability across large regions. Recognizing the varying intensity and nature of droughts based on spatio-temporal factors is crucial for developing mitigation strategies. This study aims to identify drought-prone areas in the sub-watershed of the Nira River basin in western India. We evaluated ten key parameters: NDVI, rainfall patterns, DEM, slope, land use and land cover (LULC), water harvesting structures (WHS), well distribution, geomorphology, drainage density, and lineament density. Using AHP, we created pairwise comparison matrices to establish the relative importance of each parameter, synthesizing the data into a drought severity zonation map. The map reveals that about 20% of the area faces severe drought, while around 39% falls within the moderate drought category. Villages such as Palashi, Atit, Jawale, Mirje, Lohom, and Kesurdi are in moderate drought zones, whereas parts of Ghadgewadi, Limbachiwadi, Kanheri, and Zagalwadi Karnawadi are in severe drought conditions. This mapping identifies vulnerable areas and aids in developing preparedness plans and implementing relief measures to alleviate drinking water scarcity in the affected villages, addressing the socio-economic impacts of drought and ensuring sustainable water resource management in the Nira River basin.

Keywords: Drought, Scarcity, GIS, AHP, WHS

Introduction

Droughts are among the most devastating natural disasters, significantly impacting water availability, agriculture, and socio-economic conditions. In regions like the Nira River basin in western India, where water resources are already under stress, assessing drought vulnerability is crucial for effective mitigation and resource management. Murmu et al., (2019) Recognizing the varying intensity and nature of droughts based on spatio-temporal factors is essential for developing robust mitigation strategies. Zagade, N., & Umrikar, B. (2021)

This study aims to identify drought-prone areas within the sub-watershed of the Nira River basin by integrating geospatial tools with the Analytic Hierarchy Process (AHP). Geospatial technologies such as Geographic Information Systems (GIS) provide a powerful means to analyze and visualize spatial data, while AHP allows for the systematic evaluation of multiple criteria by establishing the relative importance of each parameter through pairwise comparisons (Saaty, 1980), Saaty, T. L. (1990)

Ten key parameters were selected for this analysis: Normalized Difference Vegetation Index (NDVI), rainfall patterns, Digital Elevation Model (DEM), slope, land use and land cover (LULC), water harvesting structures (WHS), well distribution, geomorphology, drainage density Nag, S.K., & Chakraborty, S. (2003), and lineament density. Day, T.J. (1980), Strahler, A.N. (1964) These parameters are critical indicators of drought conditions and impact water availability and agricultural productivity.

This mapping not only identifies vulnerable areas but also aids in developing preparedness plans and implementing relief measures. Addressing the socio-economic impacts of drought and ensuring sustainable water resource management in the Nira River basin is essential for the well-being of the local population and the resilience of the region's agricultural sector

By leveraging the combined strengths of GIS and AHP, this study provides a detailed and actionable framework for drought management, which can be replicated in other drought-prone regions globally.

Study Area

The Nira River, originating from the Western Ghats in Maharashtra, India, flows through the districts of Pune and Satara. It serves as a vital water source for agricultural and domestic use in the region, supporting local communities along its course. The river's watershed spans approximately 1,798 square kilometers, encompassing diverse landscapes from hilly terrains to fertile plains. The Nira River originates from the western slopes of the Western Ghats, supplying essential water resources to villages and towns in its path.

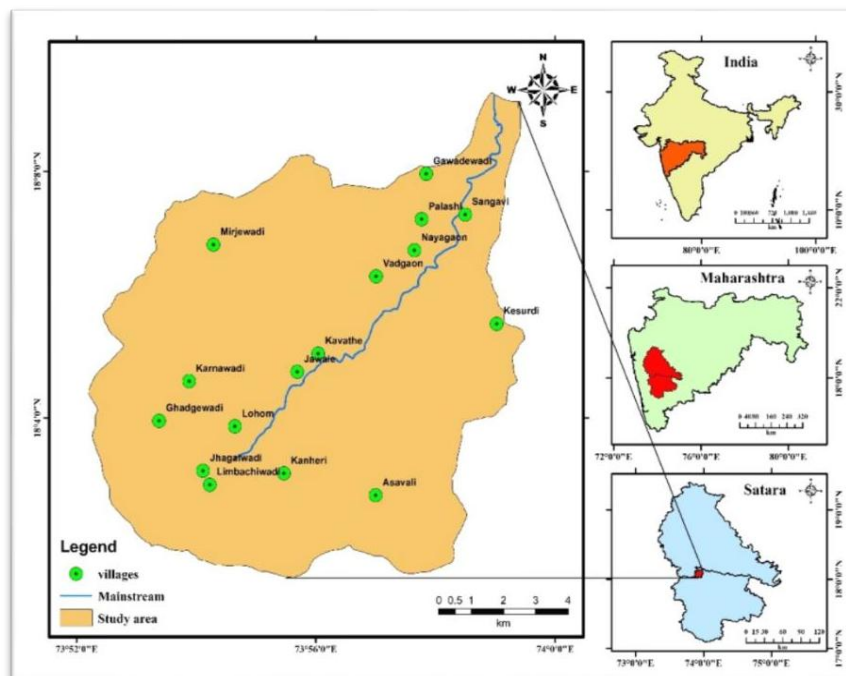


Figure 1: Location map of the study area.

Specifically, the study area encompasses parts of Khandala Taluka in Satara District and Bhore Taluka in Pune District, falling within the BM-82 sub-watershed of the Upper Bhima River basin. The region extends between latitudes 18°01'20"N and 18°09'25"N and longitudes 73°52'00"E to 74°59'30"E, encompasses a watershed region mapped by the Survey of India (SOI) on toposheet number 47F/16 at a 1:50,000 scale. Covering an area of 126.56 square kilometres, the terrain is characterized by steep and undulating landscapes. The watershed receives an average annual rainfall of 600 mm, with over 80% occurring during the monsoon season from June to September.

The climate of the area is classified as tropical sub-humid, with mean minimum and maximum temperatures ranging from 11.6°C to 37.5°C. Agricultural practices in the region are divided into two main cropping seasons: the kharif season (monsoon) from June to October and the rabi season (non-monsoon) from October to February. During the kharif season, the primary crops cultivated include paddy, maize, bajra, jowar, soybean, castor, cotton, sugarcane, turmeric, guar, and ragi. In the rabi season, the major crops are wheat, barley, peas, gram, and mustard. The typical crop rotation cycles are paddy–mustard–fallow and corn–potato–onion.

Methodology and techniques

The delineation of the watershed, encompassing an area of 126.56 sq.km, was achieved using ArcGIS tools. The drainage network was generated using Survey of India (SOI) toposheets, with stream ordering based on the Strahler method, utilizing ArcGIS and Global Mapper. The drainage network, contour map, and spot heights were derived from 1:50000 scaled SOI toposheets. Satellite data, including ASTER GDEM and CARTOSAT, were used to create a Digital Elevation Model (DEM) for generating a slope map. GIS software was employed to create a contour map from the DEM.

Morphometry, the measurement and quantitative analysis of the earth's surface configuration, including relief shape and size, provides valuable insights into basin geometry, rock hardness, structural control, erosion, and geological history (Clarke, 1966; Strahler, 1964). This analysis involves calculating parameters such as linear, areal, and watershed aspects, as well as slope contributions (Nag & Chakraborty, 2003). Morphological attributes significantly influence a basin's hydrological response and can be used to summarize its hydrological behavior.

Considering watershed characteristics, several thematic maps, such as drainage network with drainage order, soil, slope, and land use/cover, are essential. These maps are prepared using remote sensing data and/or conventional sources within a GIS environment. Critical analysis of thematic maps derived from satellite data interpretation and collateral data helps identify issues and potentials of each thematic aspect, facilitating the planning of soil and water conservation measures. A water resource development map is created by integrating these thematic layers in a GIS environment, using logical conditions to identify suitable sites for recharge in the research area.

Assigning Weightages and Weight Normalization Using the Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP), developed by Saaty (1980, 1990), is a method for pairwise comparisons used to calculate normalized weights and the geometric mean of individual parameters, thereby generating relative ratio scales from paired comparisons (Murmu et al., 2019). AHP is widely used in groundwater prediction modeling due to its precision, speed, and cost-effectiveness (Murmu et al., 2019). A key advantage of AHP is its emphasis on evaluating each individual property, facilitating robust decision-making (Saaty, 1980). In integrated analysis, assigning accurate weights to each class is essential, as the output's accuracy depends on these weights. The pairwise comparison matrix derived from ranking each influencing factor. To normalize the matrix, each entry in a column is divided by the sum of that column.

Consistency Analysis

To compute the consistency vector, the values from the pairwise comparison matrix are multiplied by the normalized pairwise matrix values of the thematic layers using matrix multiplication. The Consistency Index (CI), which measures the degree of consistency, is calculated using the formula:

$$CI = (\lambda_{\max} - n) / (n - 1)$$

Where, $\lambda_{\max}$ represents Consistency Vector and n represents number of parameters used.

The Consistency Ratio (CR) is calculated using the Consistency Index (CI) and the Random Index (RI) with the formula:

$$CR = CI / RI$$

where, RI is the Randomized Index from Saaty, 1980. A CR value of 0.1 or less is considered acceptable; a higher value necessitates a re-evaluation of the judgments. In this study, the consistency ratio was calculated to be 0.097

Weight assignment using AHP

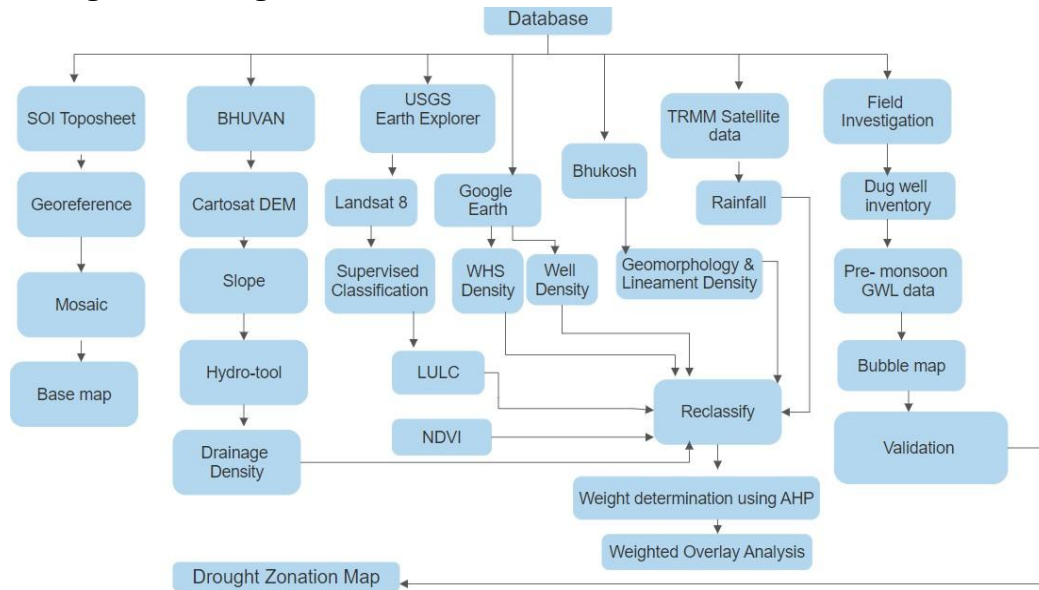


Fig. 2: Flowchart of methodology adopted to delineate the drought zones in the study area

Weighted overlay analysis

Weighted overlay analysis is a straightforward and effective method for assessing potential drought hazard areas. In this study, ten environmental factor maps were utilized to create a drought zonation map. Each factor was assigned a numerical rating from 1 to 4 based on its significance, and the classes within each factor were given weights and grades, with higher values indicating a greater impact on drought occurrence. Zagade, N., & Umrikar, B. (2021)

Using the weighted overlay method (WOM) in a Geographic Information System (GIS), these factors were combined as thematic layers to generate the drought hazard zone map. The final map was produced by summing all the parameters after multiplying them by their respective weights (refer to Eq. (1)). The resulting drought map was divided into four categories: severe, moderate, mild, and no drought.

$$D = \sum_{i=1}^n T_j \times d_i$$

----- Eq. (1)

where, T_j represents the product of the weights assigned to each parameter and the corresponding drought parameters (d_i).

Results and discussion

Thematic Maps

Slope significantly influences hydrological processes such as runoff, recharge, and storage. A slope map was created using elevation data extracted from the Advanced Spaceborne Thermal Emission and Reflection Radiometer-Global Digital Elevation Model (ASTER-GDEM). Areas with slope values between 1 and 3 are classified as gentle, indicating strong infiltration. Moderately undulating topography with slopes of 3 to 5 is assigned to the moderate class, with modest infiltration rates. Slopes between 5 and 10 are classified as moderately strong, leading to reasonably heavy runoff and poor infiltration. Slopes between 10 and 15 are classified as strong land slopes, and slopes greater than 15 are considered steep. The Naygaon Watershed study area is covered by Cretaceous-Paleocene basaltic flows, with alluvium along the riverbanks. The Geological Survey of India (GSI) conducted lithological mapping, creating a geological map at a scale of 1:25,000. The lava pile includes the Diveghat,

Purandargarh, and Mahabaleshwar formations of the Wai Subgroup in the Sahyadri group of the Deccan Trap Supergroup. The Wai Formation, the youngest, overlies the Lonavala Subgroup and constitutes over half of the Deccan basalt layer (Beane et al., 1986; Peng et al., 1994). It features simple flows with embedded flow tops, plagioclase laths, pyroxene, and olivine (Beane et al., 1986). The Wai Subgroup's flows are generally more evolved than equivalent flows, with few instances of Geochemically Primitive Basalts (GPBs) having the most advanced compositions (Beane et al., 1986). Within the watershed, three basalt types are observed: compact basalt, vesicular basalt, and unclassified basalt. Vesicular basalt, prevalent near the Nira River, has the highest recharge rate. Basalt formations display vertical and horizontal fractures and joints, indicating secondary porosity. However, the compact basalt's impermeability results in low overall porosity.

Geomorphological assessments are crucial for evaluating groundwater availability, flow patterns, and potential (Deshmukh et al., 2011). The research region features volcanic landforms such as mesas, denudational hills, and dissected plateaus. The geomorphological map shows that the Deccan plateau, characterized by weathering and erosion, covers the most area, leading to high groundwater potential along the river. Land use and land cover classification involves categorizing human activities and natural landscape components over time using scientific and statistical methods. Categories include Water Body, Agriculture, Barren Land, and Forest, providing information for analyzing the present situation. Lineaments, landscape features revealing underlying geological structures such as faults or fractures, have a density ranging from 0 to 3.23481 in the study area. The northeastern and southeastern regions show high lineament density. Drainage density, the proximity of stream channels, is measured as the total length of all order stream segments per unit area. The drainage network and density reflect lithology (Day, 1980). The observed drainage pattern is primarily dendritic, with parallel to subparallel configurations in first-order streams.

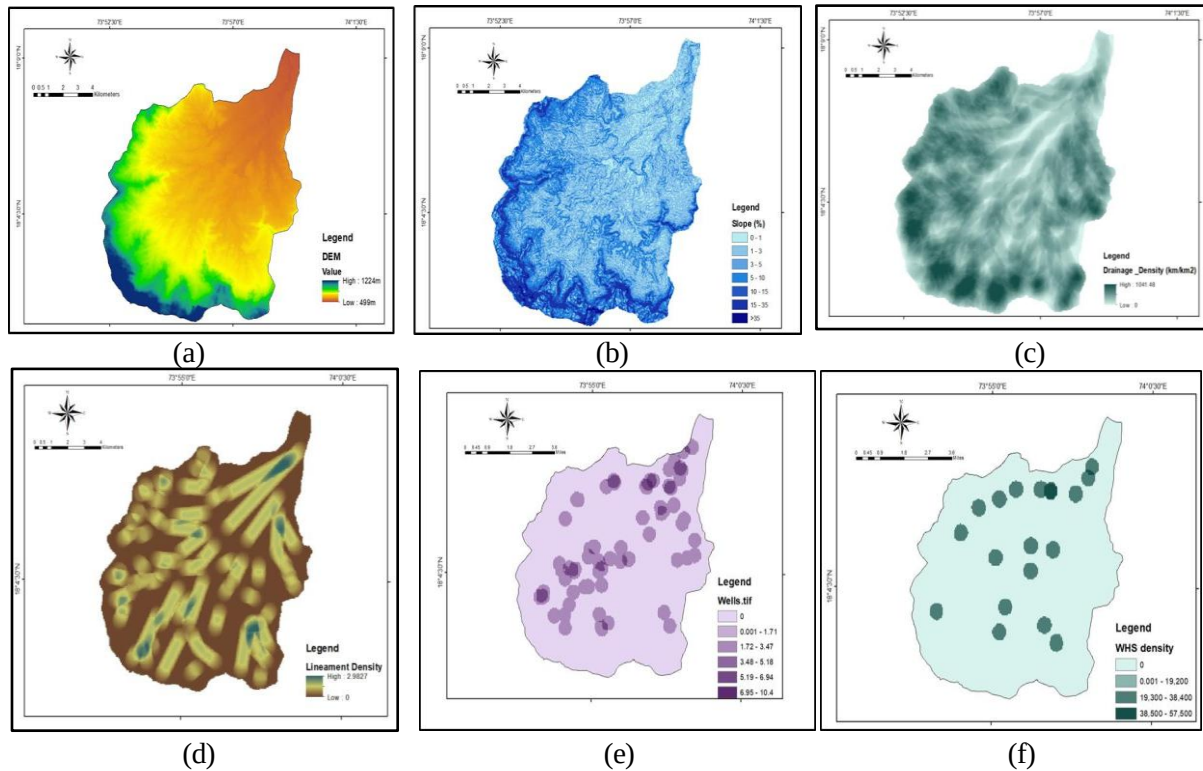


Fig. 3: (a) Elevation map of the study area; (b) Slope map of the study area; (c) Drainage Density map of the study area; (d) Lineament density of the study area; (e) Well Density map of the study area; (f) WHS density of the study area.

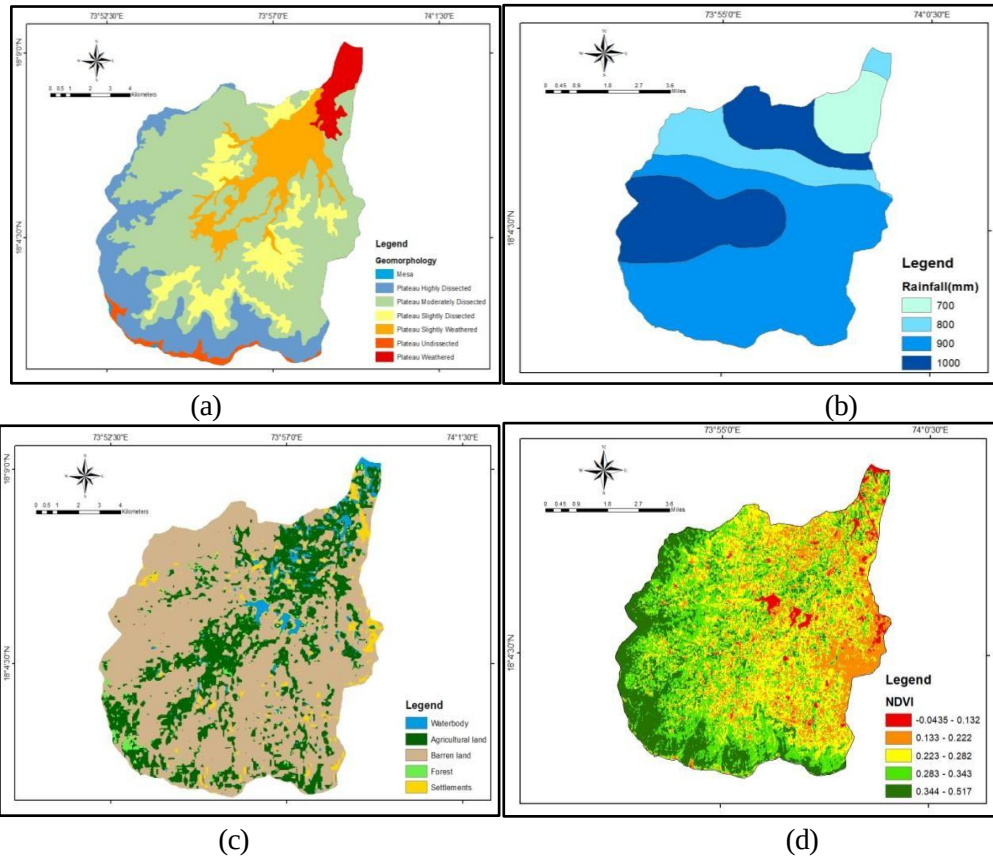


Fig. 4: (a) Geomorphology of the study area; (b) Rainfall map of the study area; (c) LULC map of the study area; (d) NDVI map of the study area.

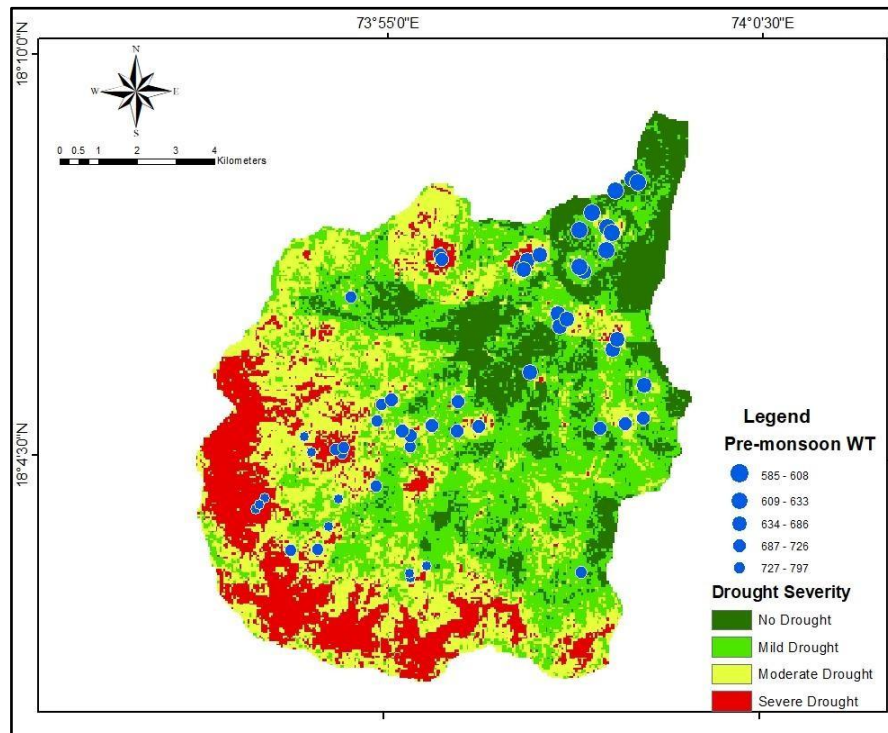


Fig. 5: Drought Zonation map of the study area

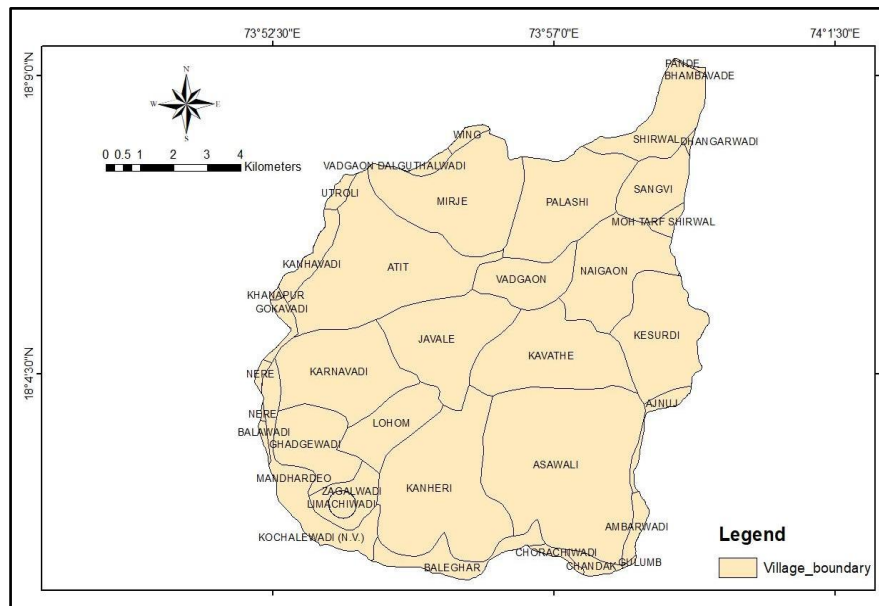


Fig. 6: Village map of the study area

Conclusion

A study was conducted in parts of the Nira river basin to explore the efficacy of integrated GIS and AHP techniques in drought hazard mapping. NDVI, rainfall, DEM, slope, LULC, well density, water harvesting structures, geomorphology, lineament density, drainage density thematic layers were considered to produce drought zonation map. This resultant map reveals that about 20% of the area is experiencing severe drought, while approximately 39% falls within the range of moderate drought. The villages namely Palashi, Atit, Jawale, Mirje, Lohom, Kesurdi fall under moderately drought zones while parts of Ghadgewadi, Limbachiwadi, Kanheri, Zagalwadi, Karnawadi are under severe drought zone. Villages located in extreme or severe drought zones face significant drinking water shortages, placing a heavy burden on government agencies to meet the drinking and domestic water needs of the population. These villages have to be provided with relief measures like piped water supply schemes, gravity-based water supply, spring water storage tanks, exploring perched aquifers, etc. The water budget exercise at village level is recommended to understand the water requirement for drinking as well as irrigation purposes and accordingly shift from cash crop to local suitable crop and less water-intensive crop to combat the scarcity. This comprehensive mapping of drought severity has the potential to aid in preparedness plan and the provision of relief measures to address drinking water scarcity in the affected villages in the study region.

References

- Murmu, P., Kumar, M., Lal, D., Sonker, I. and Singh, S. K. (2019). Delineation of groundwater potential zones using geospatial techniques and analytical hierarchy process in Dumka district, Jharkhand, India, *Groundwater for Sustainable Development*, Vol. 9, p. 100239.
- Beane, J.E., Turner, C.A., Hooper, P.R., Subbarao, K.V., & Walsh, J.N. (1986). Stratigraphy, composition, and form of the Deccan basalts, Western Ghats, India. *Bulletin of Volcanology*, 48(1), 61-83.
- Clarke, J.I. (1966). *Morphometry from Maps. Essays in Geomorphology*.
- Day, T.J. (1980). Drainage density and streamflow. *Water Resources Research*, 16(4), 919-922.
- Deshmukh, S., Pawar, N.J., & Jadhav, S.A. (2011). Geomorphological and geological controls on the occurrence of groundwater in the Deccan basalt of western Maharashtra. *Journal of the Geological Society of India*, 78(1), 56-66.

- Murmu, P., Kumar, M., Lal, D., Sonker, I., & Singh, S.K. (2019). Delineation of groundwater potential zones using geospatial techniques and analytical hierarchy process in Dumka district, Jharkhand, India. *Groundwater for Sustainable Development*, 9, 100239.
- Nag, S.K., & Chakraborty, S. (2003). Influence of rock types and structures in the development of drainage network in hard rock area. *Journal of the Indian Society of Remote Sensing*.
- Osunbitan, J.A., Oyedele, D.J., & Adekalu, K.O. (2005). Tillage effects on bulk density, hydraulic conductivity and strength of a loamy sand soil in southwestern Nigeria. *Soil and Tillage Research*, 82(1), 57-64.
- Peng, Z.X., Mahoney, J.J., Hooper, P.R., Harris, C., & Beane, J.E. (1994). A role for magmatic processes in the formation of the Deccan Trap lavas. *Earth and Planetary Science Letters*, 121(1-2), 271-286.
- Saaty, T.L. (1980). *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. McGraw-Hill.
- Saaty, T.L. (1990). *Multicriteria Decision Making: The Analytical Hierarchy Process: Planning, Priority Setting, Resource Allocation*. RWS Publications.
- Strahler, A.N. (1964). Quantitative Geomorphology of Drainage Basins and Channel Networks. *Handbook of Applied Hydrology*.
- Zagade, N., & Umrikar, B. (2021). Drought severity modeling of upper Bhima river basin, western India, using GIS–AHP tools for effective mitigation and resource management. *Natural Hazards*, 105(1), 1-24. <https://doi.org/10.1007/s11069-020-04350-9>



Evaluation of Basaltic Aquifers from Western India for Efficient Resource Management

Himanshu Gaikwad¹, Chitra Desai², Bhavana Umrikar¹

1. Department of Geology, Savitribai Phule Pune University, Pune, India
2. Department of Computer Science, National Defense Academy, Pune, India
E-mail: bnumrikar@gmail.com

Abstract

Groundwater holds a larger share of drinking and domestic supply hence its availability is crucial in achieving the goal of sustainable development of any region. Besides, if the area is covered by hard rock, then there is an upsurge in challenges to manage this precious resource. Thus, identification of groundwater potential zones (GWPZ) becomes mandatory wherein an integration of geospatial and decision support tools help gaining accuracy in demarcation. Mina river basin is one such area representing basaltic terrain has been selected to conduct the aquifer mapping. The thematic layers of various influential factors viz. rainfall, lithology, landforms, land slope, land utilization pattern, stream and lineament densities, soil, MNDWI and TWI were generated using satellite data, resource maps and topographic sheets. Raster Calculator tool is used for the integration of influential parameters after reclassifying and allocating the appropriate weightages. The resultant GWPZ map is divided into 5 classes which shows about 5 km² (14.48%), 140 km² (38.25%), 96 km² (26.23%), 58 km² (15.85%) and 19 km² (5.19%) having excellent, very good and good, moderate and poor potential zones respectively. Further, supervised data comprising the coordinates and GWP index value of 4 lakhs of records is obtained from the GWPZ map. This data is split into 70 % training and 30% testing sets, that served the purpose of training the model to identify the groundwater potential based on various input parameters. Three machine learning algorithms namely KNN, XG Boost and Random Forest were executed on the point data and it is observed that Random Forest algorithm produced 97% accurate classification of potential zones. These predicted GWP maps obtained from raster calculator and machine learning algorithms were compared with field data of groundwater fluctuation for validity. The resultant map would be a ready reckoner for the development of this precious resource and suffice the growing water demands in the area.

Keywords: GWPZ, GIS, Machine Learning, Basaltic terrain.

Introduction

Groundwater is naturally occurring hidden resource and has been a major source in catering the needs of drinking and agriculture for past hundreds of years. Groundwater being readily available through rainfall as a supplier and aquifer as a storage system, its conservation and protection is often been neglected. With increasing population, growing industries, dumping of wastes such as chemicals or even plastic is hampering the quality of our surface water resources. Hence in future to have a contamination free source of water, groundwater would play the prime role in supply side interventions. In India, especially in rural regions, groundwater is largely drawn from dug wells, mainly for agricultural and domestic purposes. To meet the increasing demands groundwater resources are exhaustively explored and this has led to various environmental problems such as groundwater depletion, water related stress, agricultural return flow leading to contamination of phreatic groundwater etc. Hence in order to avoid the exhaustion of this natural resource, there is a need of a scientific plan. The first step that involves is having a good understanding about suitable groundwater recharge sites. It helps in understanding the availability, volume, degree and source of contamination.

The emergence, storage and fluctuation of groundwater are governed by various factors such as climate, drainage network, rock/soil types, geomorphology, hydrogeology and mainly anthropogenic activities (Sabale & Thorat, 1991; Dar et al., 2010; Deshmukh, 2011; Kalpana & Elango, 2013; Gaikwad et al., 2018; Gashaw et al., 2018). The Deccan Traps having an areal extent of 500,000 km² are one of the extensive formations in which groundwater is generally found in phreatic state in weathered zones just above the hard rocks and in confined/semi-confined state in cracks, joints, fissures, secondary porosities of vesicular amygdaloidal basalts in between successive lava flow (Limaye, 2010). Groundwater recharge in Deccan basalts is not easy as it seems to be. Hence in order to decipher the groundwater potential sites a lot of researchers have adopted various techniques. Both direct and indirect techniques have been used in an approach to quantify natural groundwater regime (Scanlon et al., 2006; Mondal et al., 2012). The direct method such as tracer techniques, in which a recharge pulse is said to directly move through the pores in subsurface estimating the groundwater flow as well as potential zones. This technique has been used almost all over the world (Wright, 1964; Reznick et al., 1979; Krishnan, 2015; Sebastian et al., 2018; Hoffmann et al., 2019). Stable isotope signatures are also one of the vastly used methods to determine the source and also the age of groundwater (Terwey, 1984; Barbeta et al., 2018; Yoon et al., 2018). Water table fluctuation method (Yang et al., 2018; Bourgault, 2016; Blarasin et al., 2016; Mondal & Singh, 2004) is one of the hydrogeological approaches along with base flow separation method (Gonzales, 2009; Kouanda et al., 2018; Risser, 2009) been used to estimate the groundwater potential. In addition to this, various geophysical techniques (Shailaja et al., 2018; Maliva, 2009) especially VES surveys are beneficial in aquifer characterization. Geostatistical approach (Mallick et al., 2015) and Entropy based methods (Mondal & Singh, 2010) have also been used. However, all these methods are time consuming, expensive and cannot be carried out everywhere particularly in highly undulating basaltic topography. Groundwater potential zones were assessed with the help of geospatial modelling by many geo-scientists both in India and abroad (Jankowski, 1995; Krishnamurthy et al., 1996; Shahid et al., 2000; Sener et al., 2005; Solomon & Quiel, 2006; Magesh et al., 2012; Maggirwar & Umrikar, 2011; Nagarajan & Singh, 2009; Murthy, 2000).

Machine learning applications are broadly seen in prediction and classification of geospatial data (Tohidi et al., 2020). Several aspects related to groundwater potential have been analyzed with the help of different machine learning algorithms (Naghbi et al., 2016; Golkarian et al., 2018; Prasad et al., 2020). In this study, three machine learning algorithms namely KNN, XG Boost and Random Forest have been for identification of groundwater potential zones (GWPZ). Preparation of various themes in geospatial environment, such as geology, geomorphology, slope, land utilization pattern, drainage and lineament densities, soil type, MNDWI, TWI and rainfall with overlay analysis using machine learning algorithms help improving accuracy in identifying the groundwater prolific areas. Thus, a geospatial modelling and machine learning algorithms are jointly used in Upper Bhima catchment, Maharashtra, India for the sustainable development of groundwater resource.

Study area

The area is drained by Meena river that originates at Bhivade Kh and continues its travel through Kusur, Vadaj, Narayangoan, Ranjani, valti and finally meets river Ghod near Paragaon Shingave. The stretch of the Meena basin lies in some parts of Junnar and Ambegoan Talukas of Pune District, Maharashtra India. The areal extent of the basin is 366 sq. km with maximum elevation of 1278 m above mean sea level. It constitutes of two sub-watersheds namely BM- 7 and 8 and included in the (Survey of India) toposheet no. 47 E/12, 47 E/16, 47 I/04 and 47 J/01. It lies between 180 59' 00" and 190 14' 00" North latitudes and between 730 38' 00" and 740 05' 30" East longitudes (Fig.1). The main central location in study area is village Narayangoan situated on Pune-Nashik highway. The study area shows monsoon type of climate and the rain occurs from June to September with annual average of 497mm. The area experiences hot tropical climate with temperature rising up to 39°C in summer months of April and May. The average yearly maximum temperature is about 32°C and minimum 21°C.

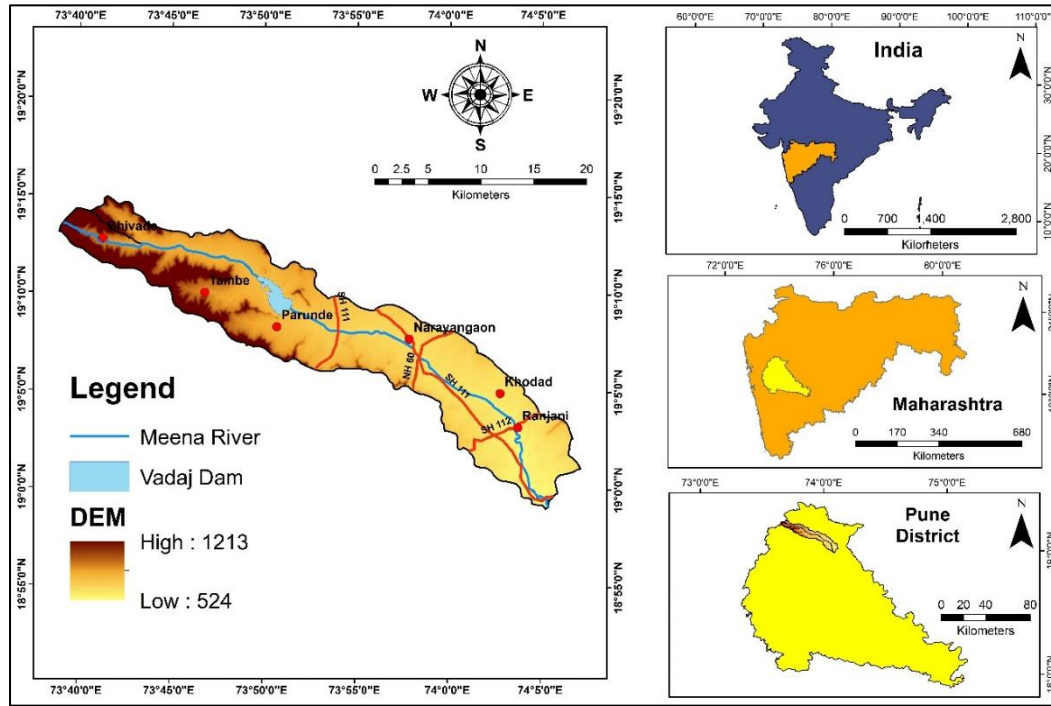


Fig 1: Location map of the study area

Methodology

Thematic layers of geology, geomorphology, slope, land utilization pattern, drainage and lineament densities, soil type, MNDWI, TWI and rainfall were generated using various RS-GIS tools assigning the UTM–WGS 84 projection and coordinate system.

Digital Elevation Model (DEM) has been subset from ASTER-GDEM data and land slopes were derived from DEM. The base map and study area boundary were generated in GIS environment for Upper Bhima Basin mosaicking the Survey of India (SoI) toposheets of 1:50,000 scale. Arc-hydro tool was employed to extract the drainage network of the upper Bhima area. Further, line density tool of Arc-GIS software was employed to obtain the drainage density map. Lineaments were extracted from Landsat 8 satellite data Band-4 (Red) using Q-GIS software. Geology and Geomorphology maps were digitized from the district resource map (DRM) of Geological survey of India (GSI, 2001). Geological traverses along the road / stream sections were taken during the field visits to understand various features of simple and compound lava flows. The outcrops, hill sections and well sections were also investigated and the geology of the study area was validated accordingly. Landsat 8 satellite image was downloaded and land utilization pattern was derived with the help of supervised classification method using ERDAS Imagine software. MNDWI map was also generated using the same Landsat8 imagery by executing the Green and SWIR band ratio algorithm. Rainfall distribution map is prepared from Tropical Rainfall Measuring Mission (TRMM) data for the year 2019. TWI map is derived using flow accumulation tool and tan slope data using the equation $TWI = \ln(a/\tan\beta)$ where 'a' is the upslope catchment area and $\tan\beta$ is the slope angle in the grid under consideration.

The rasterization with 30*30m resolution of all these themes was conducted to facilitate the weight allocation process. The ranking was given to individual sub-feature class of each theme depending on the degree of influence on groundwater availability (Table 1). The groundwater potential areas were obtained by superimposing all these thematic maps applying weighted overlay method. The resultant map generated after integration of all themes was reclassified in five categories namely 1-Poor, 2-Moderate, 3-Good, 4-Very Good and 5-Excellent.

Table 1: Assignment of ranks to feature class based on the degree of influence

Sr. No	Classes	Subclasses	Rank
1	Geology	Compact Basalt	3
		Vesicular Amygdaloidal basalt	4
		Vesicular basalt	5
2	Geomorphology	Escarpment Slope	1
		Channel Command Plateau	3
		Highly Dissected Plateau	2
		Butte	1
		Mesa	2
		Moderate Dissected Plateau	2
		Slightly Dissected Plateau	2
		Plateau shallow-weathered	4
		Plateau Undissected	5
		Waterbody	0
3	Drainage Density	Low (0 - 1.71)	5
		Moderate (1.72 - 2.62)	4
		Moderately high (2.63 - 3.56)	3
		High (3.57 - 5.46)	2
		Very high (5.47 - 9.27)	1
4	Soil	Fine Soil	3
		Clayey Soil	4
		Loamy soil	5
5	Slope	Gentle (0-5%)	5
		Moderate (5-10)	4
		Moderate strong (10-15)	3
		Strong (15-35)	2
		Steep (>35)	1
6	Rainfall	Very high (1,232 - 1,460)	5
		high (1,013 - 1,231)	4
		Moderate (855.2 - 1,012)	3
		Low (742.4 - 855.1)	2
		very Low (588.4 - 742.3)	1
7	LULC	Hills	1
		Agriculture	4
		Vegetation	5
		Barren land	2
		Fallow land	3
		Settlement	1
		Waterbody	0
8	Lineament Density	Very high (2306.7 - 3755.6)	5
		high (1522.1 - 2306.6)	4
		Moderate (901.94 - 1523)	3
		Low (340.09 - 901.94)	2
		Very Low (0 - 340.08)	1
9	MNDWI	Very high (0.07-0.21)	5
		high (-0.05- 0.06)	4
		Moderate (-0.11- -0.06)	3
		Low (-0.17- -0.12)	2
		Very Low (-0.32- -0.18)	1
10	TWI	Very high (11.25-19.27)	5
		high (8.95-11.24)	4
		Moderate (7.3-8.94)	3
		Low (5.77-7.29)	2
		Very Low (3.02-5.76)	1

Further, the latitude-longitude of each cell have been procured using ArcGIS pro. For this, the CSV file format was converted into point data using the display XY to points tool in ArcGIS Pro that generated the point shape file of 30*30m pixel resolution. To maintain the 30*30m pixel resolution for all the

datasets DEM was taken as a base file. DEM was converted into polygon using Raster to Polygon tools. The attributes having coordinates were attached to each pixel and point shape file points together using spatial join operation. The data so obtained (labelled data that includes ten influential parameters, coordinates of each cell and target variable rank i.e. groundwater potential value), have been pre-processed to be provided to the machine learning algorithm. Three algorithms viz. K-Nearest Neighbor (KNN), XGBoost and Random Forest were used to train and model the data. The train - test data has been split into 70:30 ratio for training the model. Confusion matrix and other performance metric – precision, recall, F1-score and accuracy percentage have been computed for each model. Subsequently, the model that best fits to the task of groundwater potentiality for the given data set has been identified.

Data Description

The data set consist of 10 variables with 401824 observations. There are no missing cells or duplicate rows after pre-processing of data. The total size in memory is 59.1 MiB and average record size in memory is 154.1 B. Table 2 shows the number of observations for each GWPZ class which is the target variable. Figure 1 shows the histogram of the GWPZ dataset.

Table 2: Distribution of observation for GWPZ Class

Class	No of Observations per class
1	17588
2	63955
3	108940
4	153701
5	57640

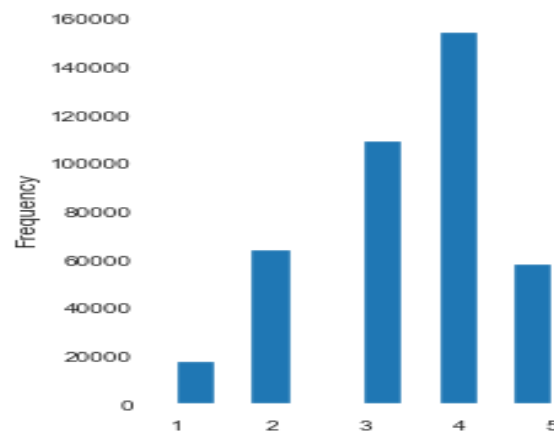


Fig 2: Histogram of GWPS data

Machine Learning Models

Machine learning is useful to build a model using features and identifying patterns, to achieve the said task with minimal human interventions. The performance and accuracy vary from model to model and the type of algorithm used to generate the model. In the present study, to understand the performance of the task i.e. classifying GWPZs based on different input features (ten influential parameters), three distance-based machine learning algorithms (KNN, ensemble method based Random forest and XGBoot – extreme gradient boosting) are applied for prediction of the groundwater potentiality in semi-arid basaltic terrain.

K-nearest neighbour (KNN) (Fix & Hodges, 1951; Altman, 1992) works on the principle of similarity supported by calculating the distance between target point location and the surrounding data points to understand the closest point for making the decision. Provided supervised learning data to KNN, a non-

parametric algorithm for classification, it assumes that class probabilities are approximately constant, which may not be true with most of the neighbourhood. The other two algorithms represent ensemble method that combine different models to improvise the results (Brown, 2010). Ensemble methods are popularly used for generating various models using adapted version of training data or simple averaging or else voting (Flach, 2012). The best-known ensemble methods are bagging (Breiman, 1996) and boosting wherein the weak learners are run independently in bagging and sequentially in boosting to enhance the results (Schapire, 2003). Thus, random forest (Ho, 1995; Breiman, 2001) has been chosen to tackle the multiclass problem for groundwater potential zonation. Also, a widely used scalable tree based boosting algorithm XGBoost (Chen & Guestrin, 2016) claims to offer state-of-art results on many problems and is also used to measure performance of various datasets.

The train: test data is split into 70:30 ratio for generating the predictive model. As most of the fields are of categorical type therefore the scaling is not performed on the training data. The algorithms are implemented using python libraries. Confusion matrix for multiclass classification (Desai, 2020) with other metrics like precision, recall, F1 score etc. are computed to evaluate the performance of the model.

KNN algorithm

In KNN, K is the positive integer that identifies K points in the training data that are closest to a particular point in test data. The value of $K=5$ has been considered in the present study. In this algorithm, X denote the features, such that, $X = (x_0, x_1, \dots, x_j)$ where j is an input variable and y denote the target variable that is groundwater potential zonation map. KNN classifies a given observation by estimating conditional distribution of y on X . The confusion matrix designed for KNN is shown in table 3 and the precision, recall, F1 score metrics for KNN are included in table 4.

Table 3: Confusion matrix (KNN)

		Predicted				
		1	2	3	4	5
Actual	1	4379	708	26	6	0
	2	761	16683	1724	149	0
	3	45	1928	28333	2248	165
	4	13	192	2397	42248	1290
	5	0	7	127	1548	15571

Table 4: Precision, Recall, F1-Score (KNN)

	Precision	Recall	F1-Score
1	0.84	0.86	0.85
2	0.85	0.86	0.86
3	0.87	0.87	0.87
4	0.91	0.92	0.92
5	0.91	0.90	0.91

XGBOOST

XGBoost technique has been chosen considering the scalability supported by the algorithm in most of the scenarios. The algorithm is implemented using scikit-learn (Pedregosa et al., 2011), which supports exact greedy algorithm that enumerates over all possible splitting points greedily. Based on the percentile of feature distribution the initial level split is obtained. Further based on aggregated statistics

best solution is chosen. The confusion matrix for XGBoost is shown in table 5 and the precision, recall and F1 score in table 6.

Table 5: Confusion matrix (XGBoost)

		Predicted				
		1	2	3	4	5
Actual	1	4276	843	0	0	0
	2	538	16816	1958	5	0
	3	31	1869	28664	2014	114
	4	0	21	2275	43164	680
	5	1	2	29	1144	16077

Table 6: Precision, Recall, F1-Score (XGBoost)

	Precision	Recall	F1-Score
1	0.88	0.84	0.86
2	0.86	0.87	0.87
3	0.87	0.88	0.87
4	0.93	0.94	0.93
5	0.95	0.93	0.94

Random Forest

Random forest method processes ensemble learning algorithm and has two components, forest comprising multiple decision trees and randomness to pick the best fitted model. The decision trees in random forest are created randomly wherein the technique was employed for selecting the root nodes where the randomness is happening while processing. As mentioned earlier, bagging (ensemble learning) is enhanced in random forest method that trains a bunch of models in a parallel way. Here each model is trained by random subset of data. Mode of all the decision trees has been considered while tackling the classification problem whereas mean of all the trees is taken for regression problem. Random forest segregates the data set in such a way that it handles biasness in the data. The larger subset will ensure to manage biasness in the distribution of the data. The confusion matrix and precision, recall, F1 score metric for random forest are shown in table 7 and 8 respectively.

Table 7: Confusion matrix (Random Forest)

		Predicted				
		1	2	3	4	5
Actual	1	4920	196	3	0	0
	2	188	18654	475	0	0
	3	1	480	31600	582	56
	4	0	1	592	45303	244
	5	0	0	24	302	16927

Table 8: Precision, Recall, F1-Score (Random Forest)

	Precision	Recall	F1-Score
1	0.96	0.96	0.96
2	0.96	0.97	0.97
3	0.97	0.97	0.97
4	0.98	0.98	0.98
5	0.98	0.98	0.98

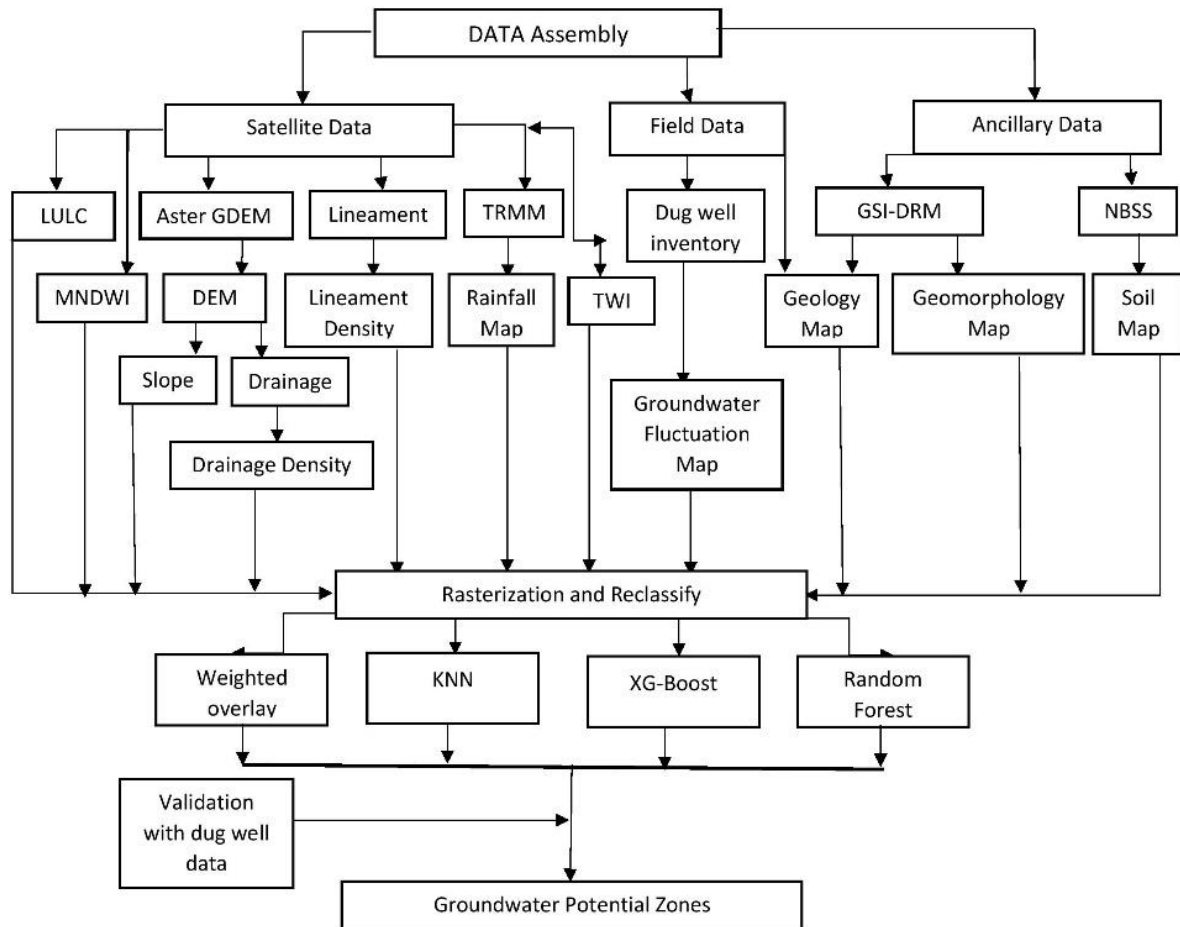


Fig. 3: Flow chart of methodology executed in present study

Results and Discussion

Geology

The area comprises a part of Upper Bhima basin and the entire area is covered by basalt lava flows of Cretaceous - Paleocene age with Quaternary alluvial and colluvio-alluvial deposits occurring along the river banks. Geological mapping of the area has been carried out by Geological Survey of India (Sabale and Thorat, 1991) and the regional geology map (1:250,000 scale) has been prepared that gives the distribution of the various geological units present in the study area (Fig. 4)

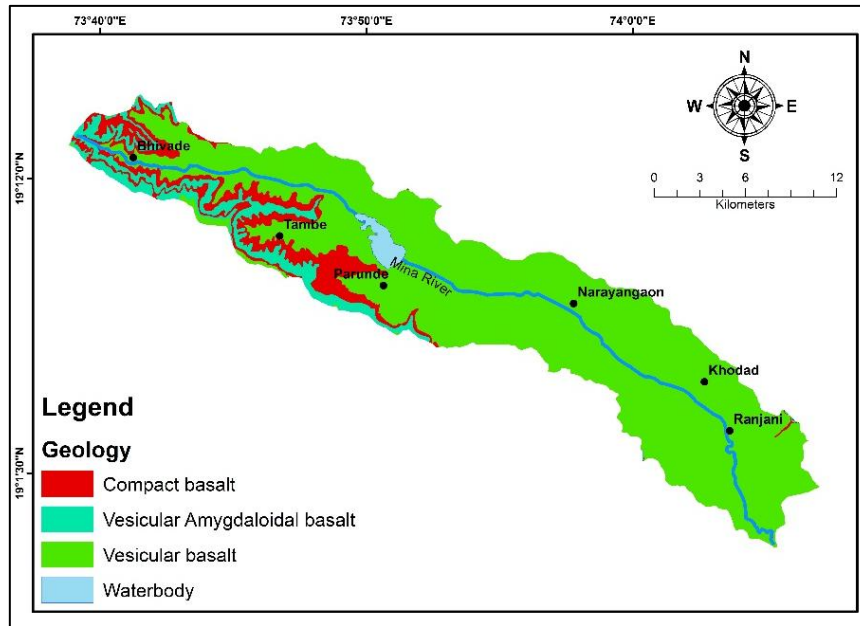


Figure 4: Major lithologic divisions in the study area.

The lava pile exposed in the area is made up of a`a and compound pahoehoe flows; that have been grouped into Ratangarh and Indrayani Formations of the Sahyadri Group of Deccan Trap Super Group. Also dissected patches of Karla Formation are observed in the NW part. The formations are separated by Megacryst M3 and Giravalli Giant Plagioclase Basalt (GPB) marker horizons. Megascopically, the flows are light to dark grey, fine to coarse grained and non- porphyritic to porphyritic. The porphyritic ones are mostly plagioclase phyric, basalts with fine to coarse phenocrysts exhibiting sparsely to moderately porphyritic texture. Jointing is common in the dense portion of the flows. The pahoehoe flows exhibit fewer regular joints as compared to a`a flows and these sheet joints are observed at the top, parallel to the flow unit. Such joints are clearly seen in the well section that exposes pahoehoe flows. The a'a flows in the area are highly jointed, forming colonnade and entablature structures. The Deccan basalts are unconformably overlain by Quaternary alluvial and alluvio-colluvial sediments that represents flood plain deposits. The Quaternary deposits are thin and occur as discontinuous patches within the river's sections. The alluvium is medium to coarse grained and calcareous in nature.

Geomorphology

Geomorphological studies are mainly based on the mapping and delineation of various landforms. It also includes the investigation of drainage characteristics of the given area. These geomorphological investigations significantly help in correlating groundwater occurrence, flow and identifying the groundwater prolific areas in the region.

Geomorphological set up is basically dependent on the factors such as climate, lithology and structure. There are different geomorphic elements observed in study area especially the landforms that are categorized into butte (B), escarpment (ES), highly dissected plateau (PLH), mesa (M), moderately dissected plateau (PLM), Slightly dissected plateau (PLS), dissected plateau (PU), weathered plateau (PLU), weathered canal command (WCC) (Fig.5). The study area is having weathered canal command as major geomorphological feature. The weathered plateau is the second highest area showing moderate infiltration capability for groundwater recharge. The mesa, butte and escarpment slope indicate poor groundwater potential.

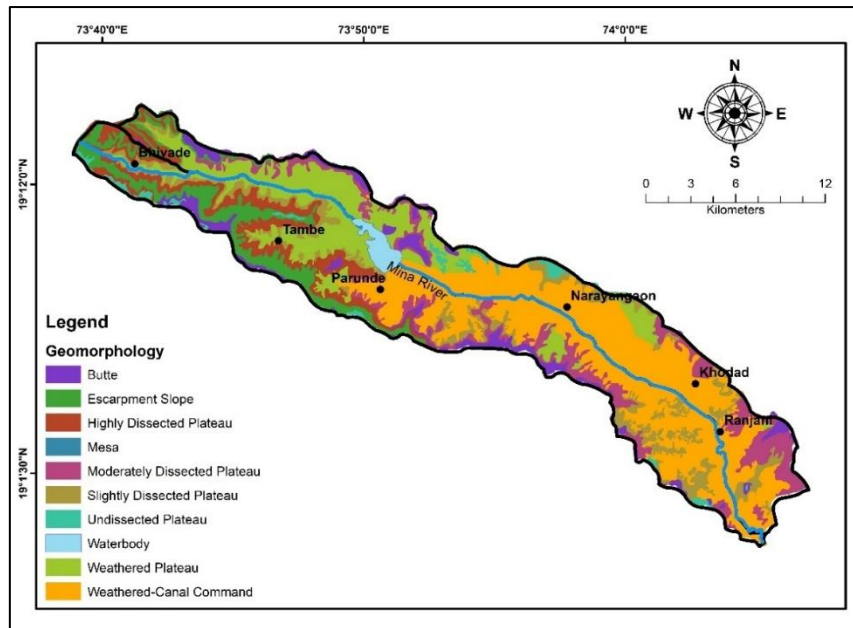


Figure 5: Geomorphology of the study area

Land use / land cover

The changing land use pattern is the prime concern of hydrogeologist, as in the phase of urbanization more and more areas are becoming impervious hampering the natural recharge process. Therefore, the knowledge of changing land use trend is essential to help quantification of runoff - recharge. Land utilization types also modify the evapotranspiration rate, generation of runoff recharge to the aquifers vis-a-vis the storage of groundwater. The land use patterns identified in the study area (Fig. 6) include hills (poor), barren land (moderate), fallow land (good), settlement (poor), agriculture (very good) and vegetation (excellent). The agricultural land is the major land use type covering plains and flat land offering ample scope for recharge of surface water.

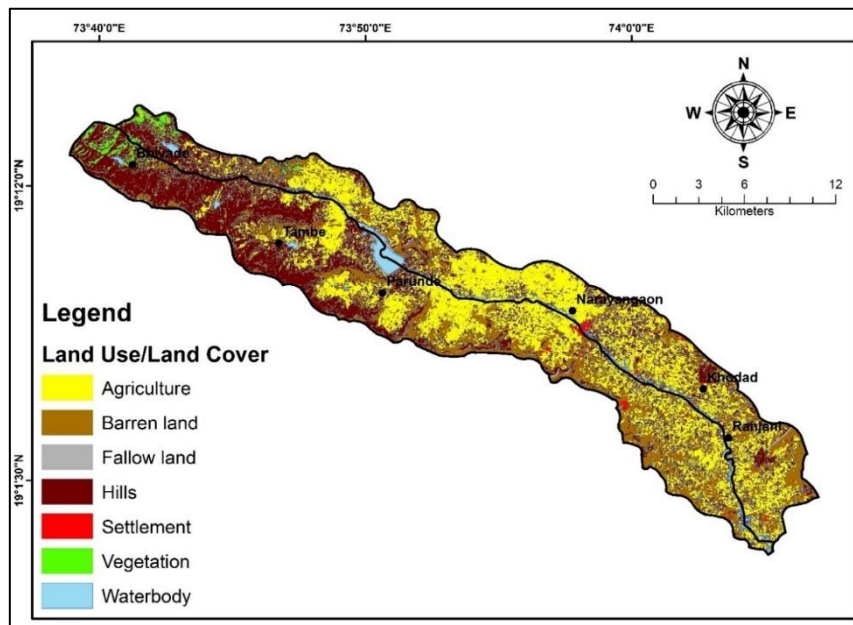


Figure 6: LULC of the Meena River basin.

Rainfall

Rainwater replenishes the phreatic aquifers in each hydrologic year and thus have an important role in determining the groundwater potentiality of any region. The study area receives precipitation from south-westerly monsoon and has been categorized into very high, high, moderate, low and very low classes. The NW part of the area receives high rainfall, whereas moderate rainfall in the central part and low rainfall in the south-eastern area (Fig. 7).

Very High rainfall region generates ample surface water that could be arrested through harvesting structures therefore, high rank is considered for very high rainfall category. The highest rainfall is occurring in source region of the study area that gets washed to low lying areas in the basin immediately resulting into low groundwater potential.

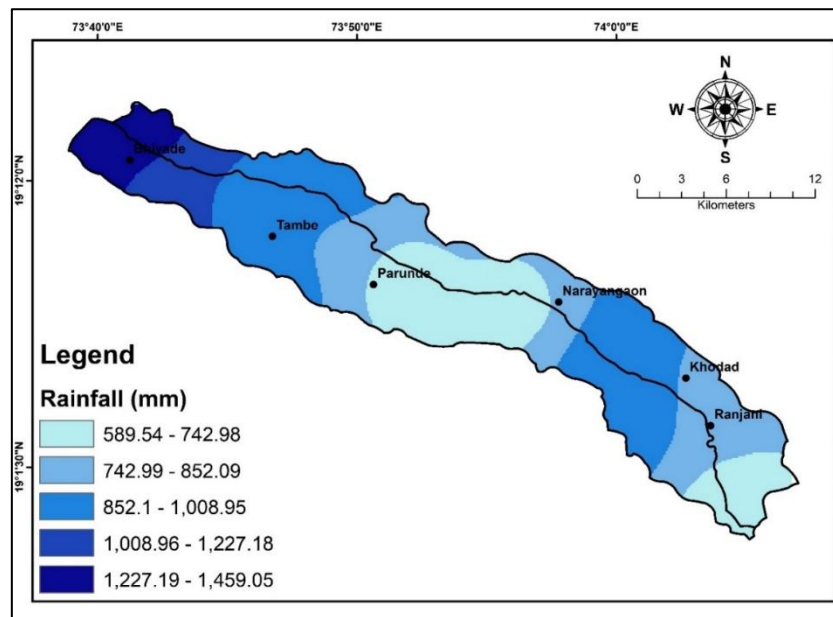


Figure 7: Rainfall distribution map of the study area

Soil

The type of soil is determined by the texture, strength and particle size distribution, etc. which further controls its water holding capacity, permeability and infiltration capacity (Singhai et al 2019). The soils in the area are derived from Deccan basalts (Fig.8).

The soils observed in the area are mostly calcareous, clayey and loamy types. If the clay content is increasing in the soil, then it slows down the infiltration rate. The soil derived from basalt generally contains montmorillonite and kaolinite minerals. Based on the properties clayey, fine and loamy soils are categorized as poor, moderate and good respectively. The upstream part of the area is having clayey soil with low groundwater potential due to less porosity; loamy soil is having porosity having capacity to infiltrate water showing high groundwater potential.

Land slope

The topographic slopes influence the land utilization pattern and land capability. The slopes also modify rainfall-runoff and rainfall-recharge ratios. Moreover, the process of mass wasting is triggered by the nature of land slopes. The velocity of surface water is high in steep slope terrain and low in gentle / flat areas.

The slope classes for the Mina river basin are 0–5%, 5 -10 %, 10-15%, 15-35% and > 35%. Majority of the area is covered by the topographic slope up to 10% and peripheral areas in the NW part being in the proximity of western Ghats are mostly steep that act as a water divide. This region receives high rainfall

and due to the steep slopes, produce high amount of surface runoff (Fig. 9). The flat areas generating less surface runoff (gentle slopes) are assumed to be favorable for groundwater and hence allotted high ranks and vice versa.

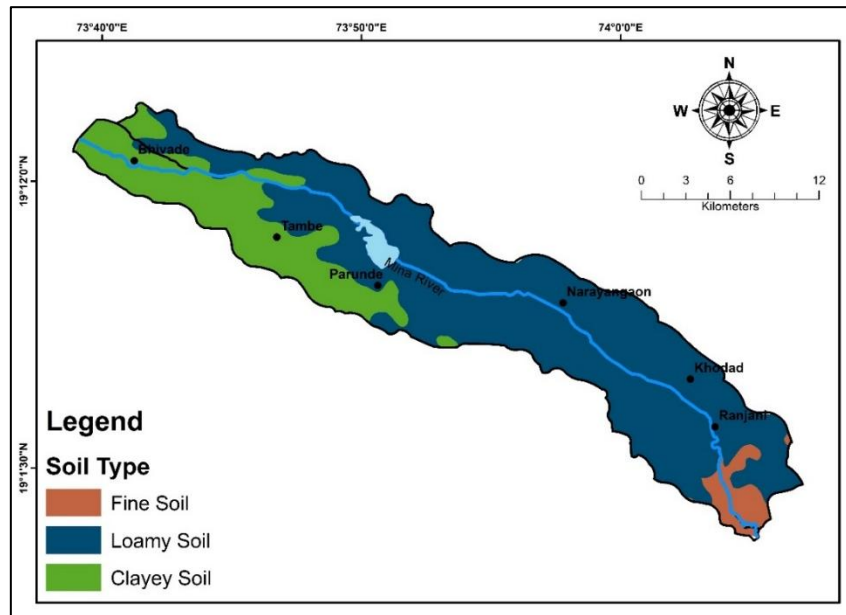


Figure 8: Soil types in Meena watershed

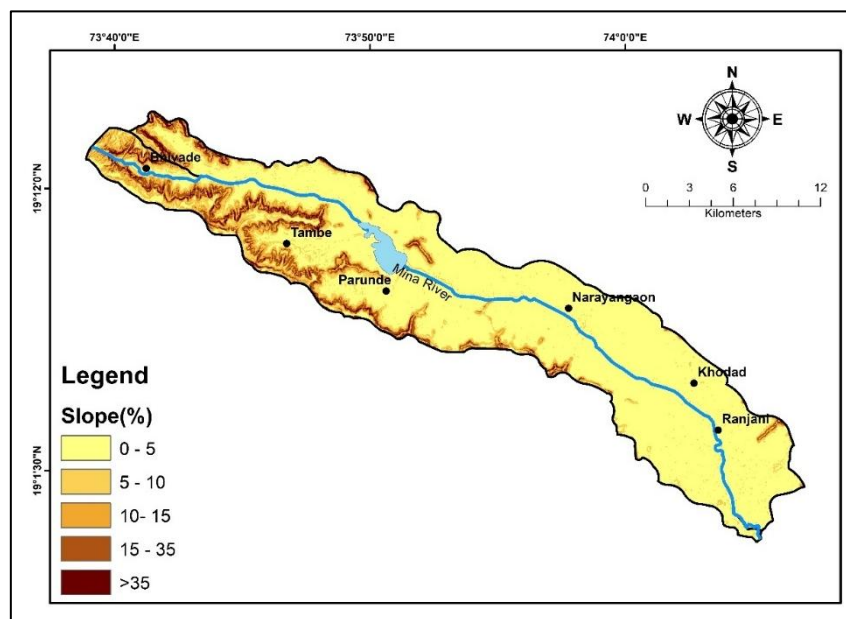


Figure 9: Slope (percentage) of the study area

Drainage density

Drainage pattern and drainage density throw light on the rock type, landform and generation of surface runoff, therefore are the essential components of groundwater potential mapping. Dendritic drainage pattern dominates the area depicting hard rock terrain with parallel / sub-parallel types at few places. The streams are sparsely placed in the central part of the area generating low density values and the classes are formulated as 0–0.17, 0.17–2.6, 2.6–3.5, 3.5–5.4 and 5.4–9.27 km/ km² (Fig 10). The high drainage density has been observed towards the northwestern part due to the proximity to western ghat hill ranges. During the field visits it was noticed that the central part covering the villages Narayangaon and Parunde have high agricultural land as well as haphazard urbanization. In this process many lower order streams have been leveled, closed or diverted. As a result, this part of the study area shows low

drainage density. Apparently, a low drainage density region gives the possibility of more infiltration as compared to a high drainage density region. Therefore, higher ranks were given to low drainage density and vice versa.

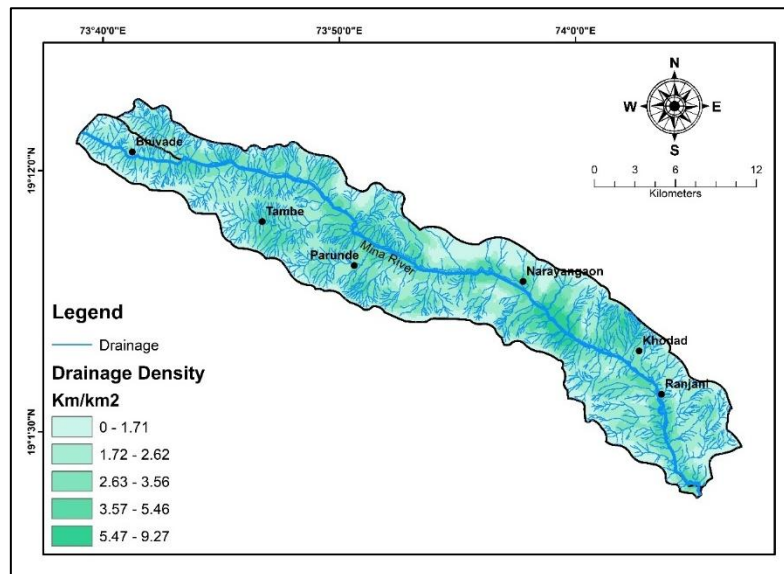


Figure 10: Drainage density superimposed with drainage network.

Lineament Density

The linear features occurring in the form of fractures, joints and dykes impart dual porosity to basaltic rock covering upper Meena river basin (Fig. 11). Dual porosity, being the function of matrix porosity and fracture porosity has bearing on the movement and occurrence of groundwater (Subba Rao et al., 2001; Sukhija et al., 2006). These lineaments have potential to establish the hydraulic connectivity between shallow unconfined and deeper confined aquifers in the area. Especially, the locations with high lineament density (Fig. 11) are vulnerable for transferring the pollutants from shallow unconfined aquifer to the deeper aquifer system. Thus, identifying the lineaments is essential while deciphering the groundwater potential zones. Total five classes namely poor, moderate, good, very good and excellent of lineament density have been formulated and maximum weight is given to the higher lineament density area being more suitable for groundwater potential.

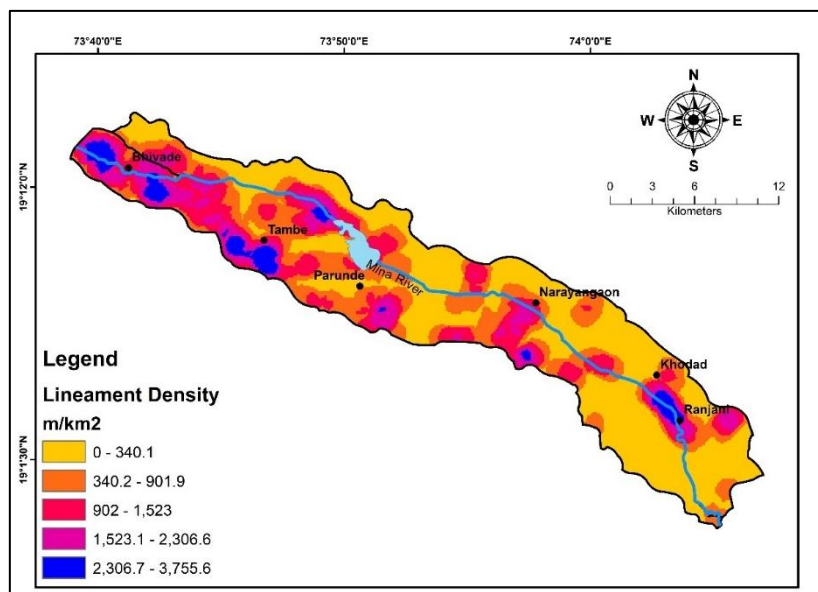


Figure 11: Lineaments density of the study area

Modified Normalized Difference Water Index (MNDWI)

This modified NDWI computed involving the Green and SWIR data of Landsat imagery significantly enhances the surface water spectral signatures on the background of other land use patterns such as built up, agriculture and fallow land (McFeeters, 1996; Xu, 2005). This index (Fig. 12) deciphered the water bodies and surface water availability in the study area. (Fig. 11). A high MNDWI value (i.e. a positive value) indicates the presence of water body whereas the negative index values depict the built up and fallow land from the study area. The northwestern peripheral areas of watershed depict low index value due to steep slopes, thin soil cover, poor green growth and high runoff. The central and eastern part of the watershed show higher values mainly because of the agricultural activities. The positive MNDWI values were allocated high ranks being favorable for groundwater potential.

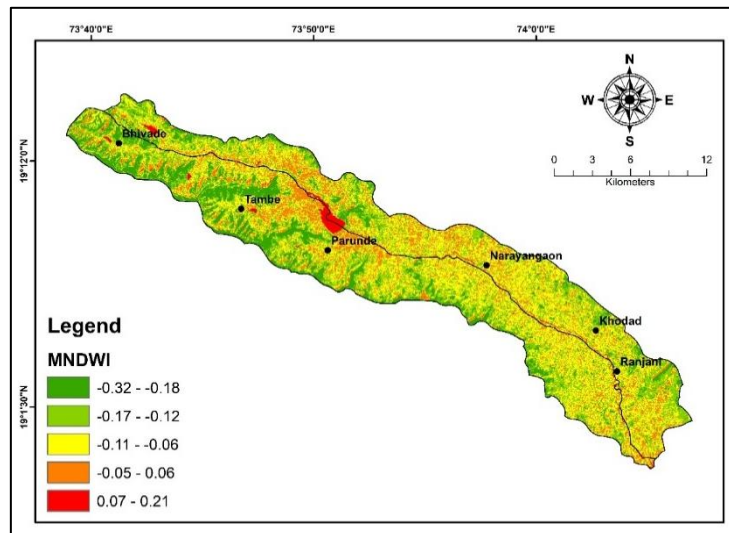


Figure 12: MNDWI map of the study area

Topographic Wetness Index (TWI)

There is about 700m elevation difference within the Meena watershed hence the TWI map has been generated for understanding the effect of undulating topography on hydrological processes, runoff flow and water accumulation (Sorensen & Siebert, 2007). This index involves the land slopes and contributing upslope area that help deciding the groundwater potentiality at various locations as well as the spatial variation in hydrological response.

The values of this index vary from 3.02 to 19.27, and further categorized into five classes: very low (3.02-5.76), low (5.77-7.29), moderate (7.3-8.94), high (8.95-11.24) and very high (11.25-19.27) (Fig. 13). The topography wetness index matches with the MNDWI values and depict lower TWI values towards northwestern peripheral part of the watershed having steep slopes, poor surface water availability and higher stream frequency whereas, the high TWI index value is mainly due to flat topography, agricultural practices and surface water harvesting structure / reservoir. Large part of the study area is under moderate TWI zone.

Groundwater Potential Zonation

The weighted overlay of groundwater influencing parameters (rainfall, LULC, soil, geomorphology, geology, lineament density, drainage density slope, MNDWI and TWI) produced the resultant potential zonation map that has been divided into 5 classes namely poor, moderate, good, very good, excellent (Fig. 14a). Groundwater fluctuation map (Fig. 15) prepared from field data is used for validating these resultant maps. The findings reveal that about 53 km² (14.48%) area is having excellent groundwater potential, 140 km² (38.25%) having very good potential zone and 96 km² (26.23%) having good groundwater potential. The favorable zone is found in the central and lowest part of the basin representing wreathed areas of alluvial/colluvial plains and farming land with 0-5% slope. The study displays that approximately 58 km² (15.85%) area having moderate potential present in middle stretch

of study area. The moderate zone is covering a small portion of basin due to the presence of dissected geomorphology, basaltic lithology moderate slope, low lineament and modest drainage density. The poor GWPZ 19 km² (5.19%) area is present mainly in upstream part of study area as it is having steep slope, high rainfall-runoff, high drainage density along with low lineament density and high elevated area. The very good and excellent zone in the study area are considered to have a major portion in the study area considering the central regions and the north eastern regions. It is mostly due to gently slopes, high lineament density and also the pattern of LULC. Subsequently, to evaluate the biasness introduced in the process of assigning weights and ranks manually to each sub-feature class and the influential parameter the machine learning algorithm were executed and the results were obtained namely for KNN (Fig. 14b), XG Boost (Fig. 14c) and Random Forest (Fig. 14d). The study revealed that the GWPZ prediction model generated through Random Forest algorithm exhibit highest accuracy (97.39) followed by XG Boost and KNN depicted the lowest accuracy.

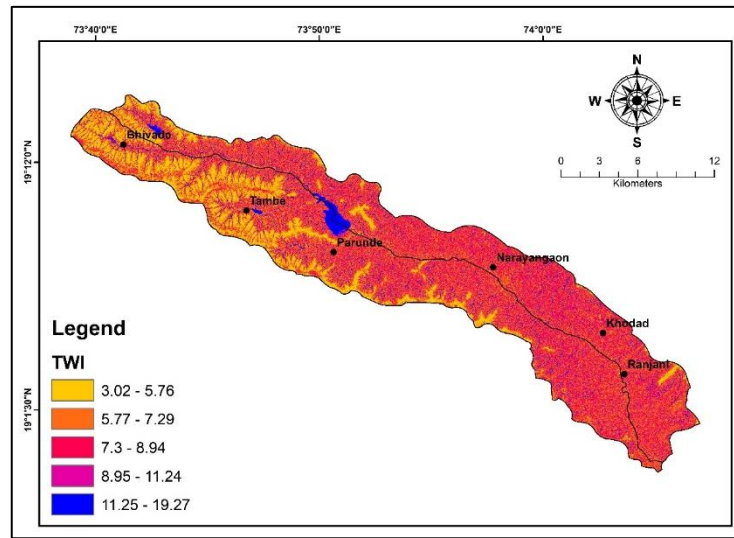


Figure 13: TWI map of the study area

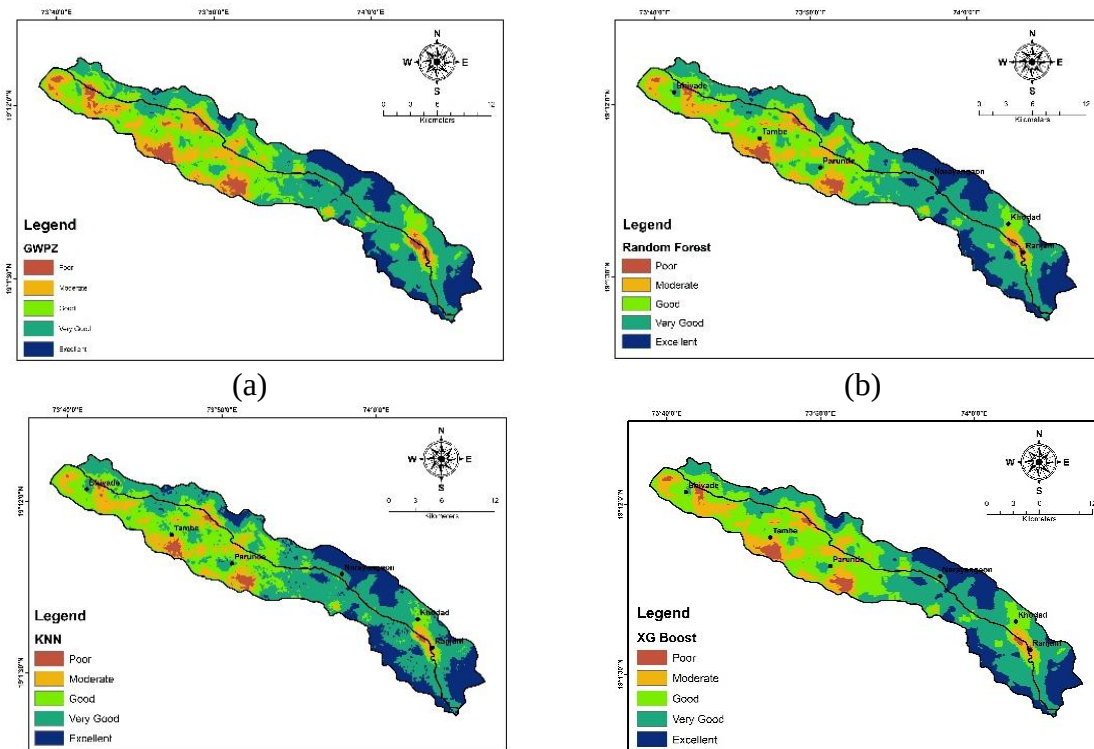


Figure 14: Groundwater potential mapping using a. Raster Overlay, b. Random Forest, c. KNN, d. XG Boost techniques.

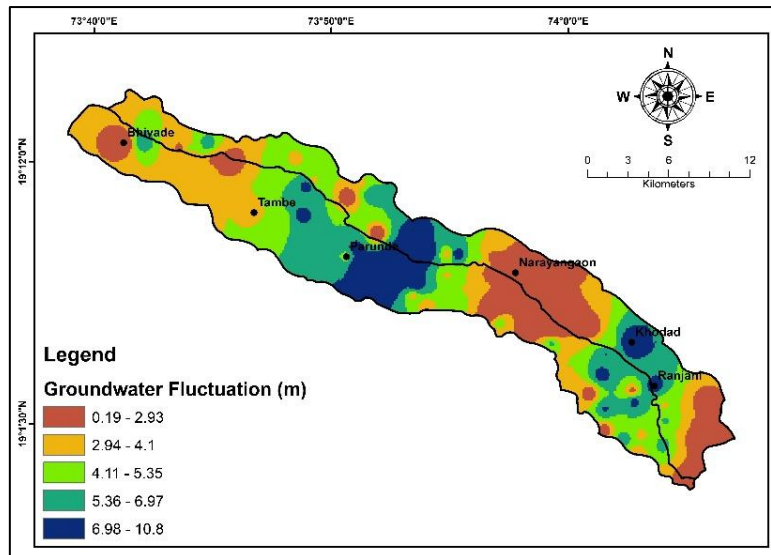


Figure 15: Groundwater Fluctuation map of the study area

Conclusion

The study primarily underlines the efficiency of RS-GIS techniques to delineate the groundwater potential in the defined watershed. The thematic layers of climatic, geomorphic, geologic and land use parameters provide the signatures that help to understand the availability of groundwater. The weights and ranks have been assigned to the influencing parameter and related sub-feature class. The resultant data has been split into 70 % training and 30% testing purposes, which is utilized for training the machine learning model to predict the GWPZ based on input parameters. KNN, XG Boost and Random Forest – three machine learning algorithms were executed, and it is observed that Random forest algorithm produced 97% accurate classification, while KNN and XG Boost predicted 88.9% and 90.4% accurate classification of potential zones respectively. The result shows that 14.48% area shows excellent potential, 38.25% area is very good potential zone and 26.23% area is good groundwater potential. The favorable zone is mainly present in the middle and lowest part having alluvial/colluvial plains and farming land with plain land. The study shows that 15.85% area having moderate potential mainly in the northwestern part of the watershed. The poor GWPZ having 5.19% area is present mainly in upstream part of study area as it is having steep slope and undulating terrain conditions. These predicted GWPZs were compared with the fluctuation of water table and it has been found that the wells from poor GWPZ are mostly dry or showing less than 1m water column in summer. Thus, GWPZ mapping with geospatial and machine learning combination can be lucratively applied in unreachable/inaccessible areas of Western Ghats, where ground data insufficiency is experienced for assessing the groundwater resource.

References

- Alizadeh, M. R., Nikoo, M. R., & Rakhshandehroo, G. R. (2017). Hydro-environmental management of groundwater resources: A fuzzy-based multi-objective compromise approach. *Journal of Hydrology*, 551, 540–554. DOI: 10.1016/j.jhydrol.2017.06.011
- Altman, N. S. (1992). An introduction to kernel and nearest-neighbor nonparametric regression. *The American Statistician*, 46(3), 175–185.
- Barbeta, A., Ogée, J., & Peñuelas, J. (2018). Stable-isotope techniques to investigate sources of plant water. In *Advances in Plant Ecophysiology Techniques* (pp. 439–456). Springer, Cham.
- Beven, K. J., & Kirkby, M. J. (1979). A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Journal*, 24(1), 43–69.
- Blarasin, M., Quinodó, F. B., Cabrera, A., Matteoda, E., Alinacastro, N., & Albo, J. G. (2016). Weekly and monthly groundwater recharge estimation in a rural piedmont environment using the water

- table fluctuation method. *International Journal of Environmental & Agriculture Research*, 2(5), 104–113.
- Bourgault, M. A., Larocque, M., & Garneau, M. (2017). Quantification of peatland water storage capacity using the water table fluctuation method. *Hydrological Processes*, 31(5), 1184–1195.
- Breiman, L. (1996). Bagging predictors. *Machine Learning*, 24(2), 123–140.
- Breiman, L. (2001). Random forests. *Machine Learning*, 45(1), 5–32.
- Brown, G., Sammut, C., & Webb, G. I. (2010). *Encyclopedia of Machine Learning*. Thomson Learning.
- Chen, T., & Guestrin, C. (2016). XGBoost: A scalable tree boosting system. In *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining* (pp. 785–794).
- Dar, I. A., Sankar, K., & Dar, M. A. (2011). Deciphering groundwater potential zones in hard rock terrain using geospatial technology. *Environmental Monitoring and Assessment*, 173(1), 597–610.
- Desai, C. (2020). Classification of orthopaedic patients based on biochemical features using machine learning algorithms. *Journal of Critical Reviews*, 7, 3823–3828.
- Deshmukh, K. K. (2011). Assessment of groundwater quality in Sangamner area for sustainable agricultural water use planning. *International Journal of Chemical Sciences*, 9(3), 1486–1500.
- Fix, E., & Hodges, J. L. (1989). Discriminatory analysis. Nonparametric discrimination: consistency properties. *International Statistical Review*, 57(3), 238–247.
- Flach, P. (2012). *Machine Learning: The Art and Science of Algorithms that Make Sense of Data*. Cambridge University Press.
- Gaikwad, H., Shaikh, H., & Umrikar, B. (2018). Evaluation of groundwater quality for domestic and irrigation suitability from Upper Bhima Basin, Western India: A hydro-geochemical perspective. *Hydrospatial Analysis*, 2(2), 113–123.
- Gashaw, T., Tulu, T., Argaw, M., & Worqlul, A. W. (2018). Modelling hydrological impacts of land use/land cover changes in the Andassa watershed, Ethiopia. *Science of The Total Environment*, 619–620, 1394–1408. DOI: 10.1016/j.scitotenv.2017.11.191
- Golkarian, A., Naghibi, S. A., Kalantar, B., & Pradhan, B. (2018). Groundwater potential mapping using C5.0, random forest, and MARS models. *Environmental Monitoring and Assessment*, 190(3), 1–16.
- Gonzales, A. L., Nonner, J., Heijkers, J., & Uhlenbrook, S. (2009). Comparison of different base flow separation methods in a lowland catchment. *Hydrology and Earth System Sciences*, 13(11), 2055–2068.
- Han-Qiu, X. U. (2005). Information extraction of water body with the MNDWI. *Journal of Remote Sensing*, 5, 589–595.
- Ho, T. K. (1995). Random decision forests. In *Proceedings of the 3rd International Conference on Document Analysis and Recognition* (Vol. 1, pp. 278–282). IEEE.
- Hoffmann, R., Uddin, W., Goderniaux, P., Dassargues, A., Maréchal, J. C., Chandra, S., ... & NILO'S, S. U. (2019). Cold water injections as innovative smart tracer technique in hot fractured aquifers. In *Groundwater Management and Governance Coping with Uncertainty* (p. 484).
- Jankowski, P. (1995). Integrating GIS and MCDM methods. *International Journal of Geographical Information Systems*, 9(3), 251–273.
- Kalpna, L., & Elango, L. (2013). Groundwater quality for drinking and irrigation in Pambar river sub-basin. *Indian Journal of Environmental Protection*, 33(1), 1–8.
- Kouanda, B., Coulibaly, P., Niang, D., Fowe, T., Karambiri, H., & Paturel, J. E. (2018). Performance of base flow separation methods. *Hydrology: Current Research*, 9(2), 300.
- Krishan, G. (2015). Environmental tracer techniques in groundwater investigations. *Water and Energy International*, 58, 57–63.
- Krishnamurthy, J., Kumar, N. V., Jayaraman, V., & Manivel, M. (1996). Groundwater potential zones through RS & GIS. *International Journal of Remote Sensing*, 17(10), 1867–1884.
- Limaye, S. D. (2010). Groundwater development in the Deccan Traps. *Hydrogeology Journal*, 18(3), 543–558.
- Magesh, N. S., Jitheshlal, K. V., Chandrasekar, N., & Jini, K. V. (2012). GIS-based morphometric evaluation of Chimmini & Mupily watersheds. *Earth Science Informatics*, 5(2), 111–121.
- Maggirwar, B. C., & Umrikar, B. N. (2011). Factors influencing groundwater fluctuations. *International Journal of Geology and Mining Research*, 3(11), 305–317.

- Maliva, R. G., Clayton, E. A., & Missimer, T. M. (2009). Borehole geophysical logging in MAR. *Hydrogeology Journal*, 17(6), 1547–1556.
- Mallick, J., Singh, C. K., Al-Wadi, H., Ahmed, M., Rahman, A., Shashtri, S., & Mukherjee, S. (2015). Groundwater potential zone delineation using geospatial methods. *Hydrological Processes*, 29(3), 395–418.
- McFeeters, S. K. (1996). NDWI for open water feature delineation. *International Journal of Remote Sensing*, 17(7), 1425–1432.
- Mondal, N. C., & Singh, V. P. (2010). Entropy-based recharge estimation in Kodaganar basin. *Current Science*, 99(11), 1560–1569.
- Mondal, N. C., & Singh, V. S. (2004). Groundwater recharge zone delineation. *Current Science*, 87(5), 658–662.
- Mondal, N. C., Singh, V. P., & Ahmed, S. (2012). Entropy-based recharge in unconfined aquifers. *Water Resources Management*, 26(9), 2715–2732.
- Murthy, K. S. R. (2000). Groundwater potential in Andhra Pradesh: A GIS approach. *International Journal of Remote Sensing*, 21, 1867–1884.
- Nagarajan, M., & Singh, S. (2009). Groundwater potential zones using GIS. *Journal of Indian Society of Remote Sensing*, 37, 69–77.
- Naghbi, S. A., Pourghasemi, H. R., & Dixon, B. (2016). Groundwater potential using BRT, CART & RF. *Environmental Monitoring and Assessment*, 188(1), 1–27.
- Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., ... & Duchesnay, (2011). Scikit-learn: Machine learning in Python. *Journal of Machine Learning Research*, 12, 2825–2830.
- Prasad, P., Loveson, V. J., Kotha, M., & Yadav, R. (2020). Machine learning in groundwater potential mapping. *GIScience & Remote Sensing*, 57(6), 735–752.
- Reznek, S., Hayden, W., & Lee, M. (1979). Fluorescein tracer technique for groundwater contamination. *Journal-American Water Works Association*, 71(10), 586–587.
- Risser, D. W., Gburek, W. J., & Folmar, G. J. (2009). Recharge estimates in Pennsylvania watershed. *Hydrogeology Journal*, 17(2), 287–298.
- Sabale, A. B., & Thorat, P. K. (1991). *Geology of parts of Pune and Ahmednagar districts*. Unpublished Progress Report for FS 1989–90.
- Scanlon, B. R., Keese, K. E., Flint, A. L., Flint, L. E., Gaye, C. B., Edmunds, W. M., & Simmers, I. (2006). Global synthesis of groundwater recharge. *Hydrological Processes*, 20(15), 3335–3370.
- Schapire, R. E. (2003). The boosting approach to machine learning. *Nonlinear Estimation and Classification*, 149–171.
- Sebastián, C., Maguiña, J., & Maghella, G. (2018). Flow velocity determination using tracer techniques. *Journal of Chemistry and Chemical Engineering*, 12.
- Sener, E., Davraz, A., & Ozcelik, M. (2005). GIS and remote sensing for groundwater investigations. *Hydrogeology Journal*, 13(5–6), 826–834.
- Shahid, S., Nath, S. K., & Roy, J. (2000). Groundwater potential modelling using GIS. *International Journal of Remote Sensing*, 21(9), 1919–1924.
- Shailaja, G., Kadam, A. K., Gupta, G., Umrikar, B. N., & Pawar, N. J. (2019). Integrated geophysical & geospatial analysis for groundwater. *Hydrogeology Journal*, 27(2), 639–654.
- Singhai, A., Das, S., Kadam, A. K., Shukla, J. P., Bundela, D. S., & Kalashetty, M. (2019). Rainwater harvesting zone identification. *Environment, Development and Sustainability*, 21(2), 777–797.
- Solomon, S., & Quiel, F. (2006). Remote sensing & GIS-based groundwater study in Eritrea. *Hydrogeology Journal*, 14(6), 1029–1041.
- Sørensen, R., & Seibert, J. (2007). DEM resolution effects on TWI. *Journal of Hydrology*, 347(1–2), 79–94.
- Subba Rao, N., Chakradhar, G. K. J., & Srinivas, V. (2001). Groundwater potential zones using remote sensing. *Journal of Indian Society of Remote Sensing*, 29(1–2), 69–78.
- Sukhija, B. S., Reddy, D. V., Nagabhushanam, P., Bhattacharya, S. K., Jani, R. A., & Kumar, D. (2006). Recharge processes in fractured granites using isotopes. *Hydrogeology Journal*, 14(5), 663–674.
- Terwey, J. L. (1984). Isotopes in groundwater hydrology. In *Proceedings of Challenges in African Hydrology and Water Resources*.

- Tohidi, N., & Rustamov, R. B. (2020). Machine learning in GIS for megacities. *Geographic Information Systems in Geospatial Intelligence*. IntechOpen.
- Wright, E. (1964). Tracer techniques in hydrology. *Nature*, 202(4939), 1254–1255.
- Xu, H. (2006). Modification of NDWI for enhanced open water extraction. *International Journal of Remote Sensing*, 27(14), 3025–3033.
- Yang, L., Qi, Y., Zheng, C., Andrews, C. B., Yue, S., Lin, S., ... & Li, H. (2018). Modified WTF method for regional groundwater discharge. *Water*, 10(4), 503.
- Yoon, Y. Y., Kim, Y. C., & Lee, K. Y. (2018). Artificial recharge using natural isotope tracers. *Journal of Radioanalytical and Nuclear Chemistry*, 318(3), 2213–2218.



Delineation of Groundwater Potential Zones using Remote Sensing and GIS: A Case Study from Ghatkesar, Telangana

Shaik Saleemmiya

Ace Engineering College, Hyderabad, Telangana, India
E-mail: saleemmiya2007@gmail.com

Abstract

Groundwater resources in the Ghatkesar sector of Telangana have come under increasing stress owing to urban expansion, intensified agriculture, and variability in monsoonal rainfall. A comprehensive geospatial framework was applied to delineate groundwater potential zones by integrating multi-source datasets, including remote sensing imagery, topographic sheets, and hydrogeological records. Thematic layers representing slope, drainage density, lineament frequency, soil characteristics, land use/land cover, and rainfall distribution were generated and evaluated using a weighted overlay technique in GIS. The resulting zonation highlighted three distinct categories: areas of high potential dominated by valley fills and pediplains, moderate potential zones associated with weathered pediments and cultivated land, and low potential sectors confined to structural hills and residual uplands. The spatial analysis underscores the importance of secondary porosity features such as fractures and lineaments in controlling recharge dynamics. Strategic interventions, particularly percolation tanks, check dams, and recharge shafts, are recommended in moderate- and low-yielding zones to enhance aquifer sustainability. The outcomes affirm the utility of geospatial tools in groundwater assessment and provide a decision-support framework for sustainable water resource management in semi-arid hard rock terrains.

Keywords: Groundwater potential, Weighted overlay, GIS, Telangana

Introduction

Groundwater constitutes one of the most critical renewable natural resources supporting life systems, economic development, and ecological balance across the globe. Despite the apparent abundance of water on Earth, nearly 97% of this resource exists as saline water in oceans and seas, while less than 3% qualifies as freshwater. Even within this small fraction, the majority is locked in ice caps, glaciers, and inaccessible deep aquifers. As a consequence, the proportion of freshwater that is directly available for anthropogenic use—through rivers, lakes, soil moisture, and shallow groundwater—remains minuscule, often estimated at less than 0.5% of the total global water reserve. Groundwater, therefore, plays a disproportionately large role in sustaining human needs, accounting for nearly 40% of irrigation water supply and more than 90% of accessible freshwater reserves. Its role becomes particularly vital in semi-arid and arid environments where surface water is limited, seasonal, or unreliable.

India's hydrological setting presents a paradox of abundance and scarcity. The country receives an average annual rainfall of about 1170 mm, translating into nearly 4000 billion cubic meters (bcm) of precipitation. However, losses due to evapotranspiration and surface runoff restrict the utilisable water potential to about 1122 bcm, of which only 432 bcm can be developed from groundwater. This figure, while seemingly large, is unevenly distributed spatially and temporally. Semi-arid tracts in the Deccan plateau, western Rajasthan, and central India frequently experience scarcity, while alluvial plains along the Ganga–Brahmaputra basin show comparatively higher availability.

Groundwater resources provide drinking water to nearly 80% of rural households and over 50% of urban populations in India. Agriculture remains the largest consumer, with approximately 65–70% of

irrigation demand being fulfilled through wells and tube wells. Yet, the rate of abstraction has exceeded natural recharge in several regions. The Central Ground Water Board (CGWB) has repeatedly warned of declining water levels in many assessment units, classifying them as over-exploited or semi-critical. In the state of Telangana alone, the utilisable groundwater potential has been estimated at 2.21 million hectare-meters annually, with nearly one-third already withdrawn. Increasing demand from domestic, industrial, and agricultural sectors continues to exert immense pressure, raising concerns of aquifer depletion, quality deterioration, and long-term sustainability.

The Deccan plateau, which covers large parts of peninsular India, including Telangana, is predominantly underlain by crystalline basement rocks such as basalts and granites. These formations are inherently low in primary porosity; groundwater occurrence is largely controlled by secondary features including weathering, fracturing, jointing, and lineament zones. Storage capacity and transmissivity are therefore highly variable, often restricted to shallow depths. Seasonal recharge is the dominant mechanism, primarily occurring during the southwest monsoon. Consequently, groundwater availability in hard rock terrains is spatially heterogeneous, temporally fluctuating, and acutely sensitive to land use practices and rainfall distribution.

Unplanned urban expansion further complicates recharge dynamics. Rapid paving of surfaces reduces infiltration, while extraction through bore wells, often deeper than 150–200 m, exceeds sustainable yield. Over time, this creates a declining trend in water levels, leading to increased costs of pumping, failure of shallow wells, and in certain cases, degradation of water quality due to up-coning of saline or mineralized water. Thus, hard rock terrains require specialized approaches for assessment and management, relying on the integration of geological, geomorphological, hydrological, and geospatial datasets.

Rapid urbanization in and around Hyderabad, including the Ghatkesar region, has exerted significant stress on local aquifers. Expansion of built-up land reduces natural infiltration by replacing permeable surfaces with impervious pavements and rooftops. Simultaneously, groundwater abstraction through deep bore wells has accelerated to meet domestic and industrial demand. Agricultural intensification further amplifies the pressure, with farmers often resorting to high-capacity pumping during dry spells. These practices disturb the natural equilibrium between recharge and discharge, resulting in persistent declines in water levels.

Traditional groundwater surveys, although detailed, are constrained by spatial coverage and temporal frequency. Remote sensing and Geographic Information System (GIS) technologies provide a complementary and cost-effective alternative, enabling synoptic analysis across heterogeneous terrains. Satellite data facilitate the extraction of critical thematic layers—land use/land cover, geomorphology, drainage, lineaments, and soil moisture—that collectively influence groundwater occurrence. GIS offers a platform to integrate these layers, assign relative weights based on hydrogeological significance, and generate composite maps delineating potential zones.

Weighted overlay analysis has emerged as a widely applied method in this context. By assigning importance scores to parameters such as slope, drainage density, soil type, rainfall distribution, and geological structures, the method allows multi-criteria evaluation of groundwater prospects. The resulting maps not only depict areas of high, moderate, and low potential but also provide a scientific basis for identifying recharge sites and planning well locations. The approach is particularly effective in hard rock terrains where subsurface heterogeneity complicates direct interpretation.

Ghatkesar Mandal, located approximately 40 km east of Hyderabad within the Ranga Reddy district, represents a rapidly transforming peri-urban landscape. The area is underlain by Archean granites with intrusions of dolerite dykes, overlain in places by weathered mantles. Groundwater levels fluctuate markedly between seasons, typically ranging from 2–8 m below ground level during the monsoon to 10–15 m during the pre-monsoon summer. The region receives an average annual rainfall of 750–900 mm, concentrated between June and September, rendering recharge both seasonal and highly variable.

The land use mosaic includes agricultural fields, settlements, industrial clusters, and small forest patches. Population growth and infrastructural development have accelerated water demand, while simultaneously diminishing natural recharge through surface sealing. The combination of semi-arid climate, crystalline geology, and rapid urbanization creates a critical need for systematic groundwater assessment.

The present study aims to delineate groundwater potential zones within the Ghatkesar region through the integration of remote sensing and GIS techniques. Specific objectives include:

- Generation of thematic maps representing slope, drainage density, soil, lineaments, rainfall, land use/land cover, and geology.
- Assignment of hydrogeological weights and integration of layers through weighted overlay analysis.
- Identification of zones categorized as good, moderate, and poor in terms of groundwater potential.
- Suggestion of suitable artificial recharge interventions in less favourable zones.

The scope extends beyond academic interest, offering a decision-support tool for planners, engineers, and water managers in Telangana. The methodology also provides a transferable framework applicable to other semi-arid hard rock terrains across India and beyond.

Study Area

Ghatkesar Mandal lies in the eastern sector of Ranga Reddy district, Telangana, approximately 40 km east of Hyderabad. The region occupies a transitional landscape shaped by plains, agricultural fields, and residual hills. Its proximity to Hyderabad has accelerated demographic growth, urban expansion, and infrastructural development, making groundwater the principal source of domestic and agricultural supply. Climatically, the Mandal experiences semi-arid conditions with hot summers, relatively mild winters, and a pronounced monsoonal regime. The southwest monsoon, commencing in early June, accounts for more than three-quarters of the annual precipitation, with July and September representing peak rainfall months. Seasonal variations strongly control recharge, while humidity, cloud cover, and wind regimes reflect the dynamic interplay of regional climate drivers.

Topographically, the terrain presents undulating pediplains interspersed with structural hills and elevated ridges. These landforms regulate drainage, erosion, and soil distribution, shaping agricultural potential and recharge capacity. The soils are dominated by loam-clay types with moderate to low permeability, supporting both rain-fed and irrigated agriculture. Hydrologically, the area is drained by a network of streams and seasonal channels linked to local watersheds, which supply irrigation and domestic needs. Hydrogeologically, the Mandal is underlain by Archean granites with dolerite dykes and quartz intrusions. Groundwater occurs primarily in weathered and fractured zones, with water levels fluctuating between 2–8 m during the monsoon and 10–15 m in the summer months. This variability underscores the limited storage and recharge potential typical of crystalline hard-rock terrains.

Socio-economically, Ghatkesar is characterized by a mixed rural–urban landscape, where population growth and land use change place increasing demands on natural resources. Settlements and agricultural land dominate the region, while elevated terrain and hills contribute to its physiographic diversity and ecological setting. All villages in the Mandal are supplied with drinking water, primarily sourced from open wells, hand pumps, and piped connections. Understanding the interplay of geology, climate, land use, and socio-economic pressures is crucial for evaluating groundwater dynamics and framing sustainable water resource management strategies in this rapidly transforming peri-urban environment.

Methodology

The research followed a multi-step approach integrating remote sensing, field observations, and GIS spatial modeling:

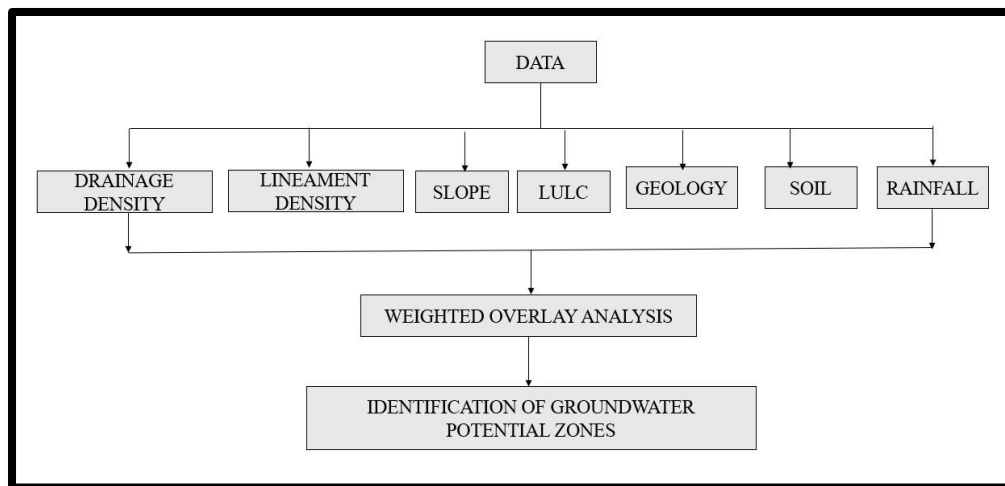


Fig 1: Flow map

The methodological framework adopted for groundwater potential assessment in Ghatkesar Mandal was structured into four sequential stages. The first stage involved the creation of a comprehensive spatial database through base map preparation and data acquisition. Survey of India (SOI) topographic sheets at a 1:50,000 scale provided detailed information on terrain configuration, drainage patterns, and surface features. High-resolution IRS P6 LISS IV MX satellite imagery was used to enhance the spatial dataset, supplying contemporary details on land cover and land use dynamics. Ancillary information, including land utilization survey records and geological maps, enriched the database by characterizing lithology, structural elements, and land use practices. Ground-truth surveys were undertaken to validate remote sensing interpretations and to record field-based hydrogeological observations. Together, these inputs established a robust geospatial foundation for subsequent analysis.

The second stage emphasized the generation of a Digital Elevation Model (DEM) from digitized contour data. The DEM provided a three-dimensional representation of terrain that was critical for deriving slope, aspect, flow accumulation, and stream ordering. These parameters served as proxies for surface runoff behaviour and infiltration potential. Areas with gentler gradients were assumed to favour recharge, whereas steeper terrains were interpreted as zones dominated by runoff. The DEM analysis thus provided an essential framework to understand the hydrological functioning of the landscape and to guide the spatial integration of other thematic parameters.

The third stage consisted of digital image processing and the creation of thematic layers. Satellite data underwent geo-referencing, geometric correction, and supervised classification to delineate distinct land cover categories such as agriculture, forest, settlement, and water bodies. Additional thematic layers—including geology, lineament density, soil distribution, rainfall, and drainage density—were prepared using both remote sensing interpretation and secondary datasets. Structural elements such as lineaments were mapped to highlight fracture zones with higher groundwater storage potential. To account for anthropogenic pressures, buffer maps were generated for agriculture and settlement zones, thereby quantifying their influence on groundwater dynamics. This stage ensured that the spatial heterogeneity of natural and human factors was comprehensively represented.

The fourth and final stage involved integration and analysis of thematic layers using GIS-based overlay techniques. Each thematic input was assigned a relative weight according to its hydrogeological significance, with parameters such as slope, geology, and lineament density given higher priority. Weighted overlay analysis was performed to identify intersections of favourable conditions, thereby delineating groundwater potential zones. The final composite map classified the region into high, moderate, and low groundwater potential categories. This output provided a spatially explicit decision-support tool, enabling planners and water managers to prioritize recharge interventions, regulate extraction, and identify sites suitable for sustainable groundwater development.

Results and Discussion

Drainage density

In this study, drainage density was derived from Digital Elevation Model (DEM) data using flow accumulation and stream-order tools in ArcGIS. Stream networks were delineated, and their cumulative length normalized by the area of the study region to generate a drainage density map. The classification revealed zones of high drainage density characterized by well-developed channel networks, particularly in central and southern portions of the Mandal, where surface water routing is efficient and the potential for localized recharge is enhanced. Areas of low drainage density, concentrated in upland and residual hill zones, indicate subdued surface drainage and comparatively limited groundwater recharge potential. Incorporating drainage density into weighted overlay analysis with other thematic layers, such as slope, soil, and lineament density, provides a comprehensive framework for identifying groundwater potential zones and prioritizing recharge interventions. The drainage density map of Ghatkesar Mandal illustrates the spatial variability of stream networks derived from Digital Elevation Model (DEM) analysis. The legend categorizes drainage density into nine classes ranging from 0.0–0.50 km/km² (very low) to 4.05–4.55 km/km² (very high). Areas shaded in dark blue represent regions of minimal drainage development, indicating subdued runoff and limited surface dissection, typically associated with uplands or residual hill terrain. In contrast, zones shaded in orange to red correspond to high drainage density, concentrated in valley systems and lower-lying plains, where well-developed stream networks facilitate efficient surface runoff.

The central, southern, and northeastern parts of the Mandal show relatively higher drainage density, suggesting greater potential for localized recharge where streams intersect with permeable formations. Conversely, peripheral upland areas dominated by lower drainage density indicate limited infiltration opportunities and reduced groundwater prospects. This spatial distribution underscores the hydro-geomorphic control on groundwater availability, and the map serves as a crucial thematic input for delineating groundwater potential zones when integrated with slope, geology, soil, and land use/land cover data.

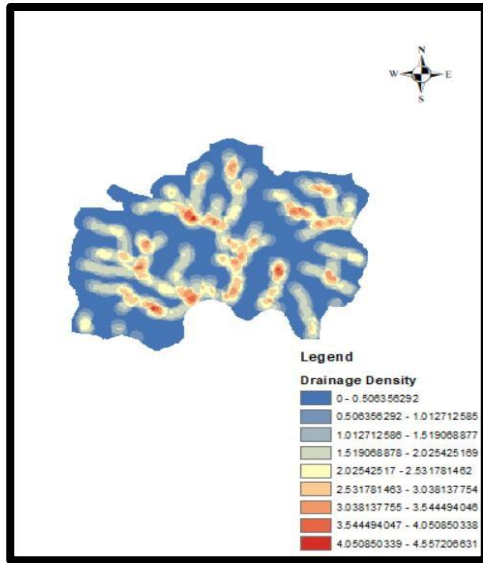
Lineament density

The lineament density map of Ghatkesar Mandal illustrates the distribution and concentration of structural features such as faults, fractures, and joints, which are critical pathways for groundwater movement and storage in crystalline hard rock terrains. Lineament density values range from 0.0–0.88 km/km² (very low) to 3.55–4.44 km/km² (very high). Areas shaded in dark green correspond to zones of low density, indicating limited structural control on groundwater occurrence. In contrast, yellow to red zones denote progressively higher densities, representing regions where fractures and lineaments are more abundant, enhancing secondary porosity and permeability.

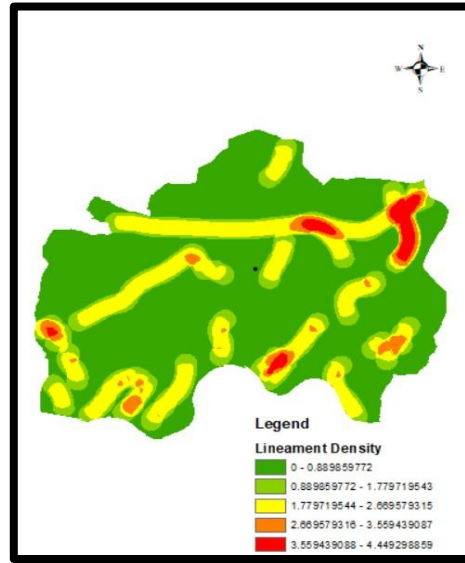
High lineament density is observed predominantly in the central, southeastern, and southwestern sectors of the Mandal, reflecting zones of intense structural activity. These areas are hydrogeologically significant, as fractures and joints act as conduits for infiltration and groundwater storage. The integration of this thematic layer with slope, soil, and drainage density maps provides a more robust understanding of aquifer potential. Consequently, the red and orange zones highlighted in the map are considered favourable for groundwater exploration and suitable locations for artificial recharge interventions such as recharge shafts and percolation tanks.

Slope

The slope map of Ghatkesar Mandal, derived from the Digital Elevation Model (DEM), illustrates terrain gradients ranging from 0–1.24° (nearly flat) to 31.70° (steep). The legend classifies the landscape into nine slope categories. Predominantly, the region is covered by gentle slopes (0–5.8°), represented in light to dark green shades, which dominate the central and southern areas. These gentle slopes are hydrogeologically significant because they favour infiltration and groundwater recharge by reducing surface runoff.



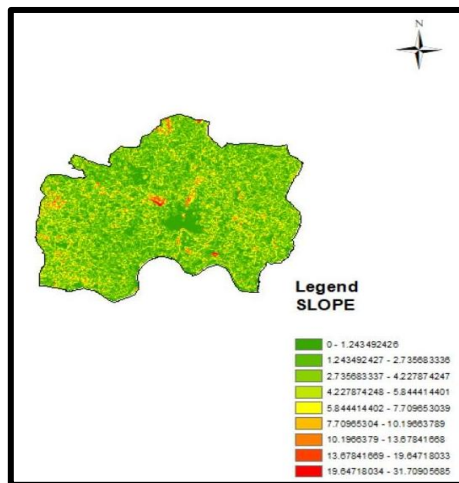
(2)



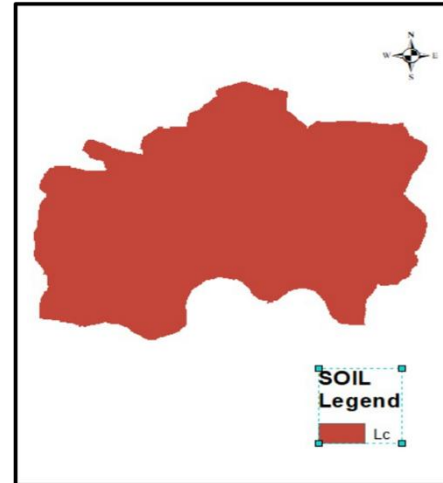
(3)

Fig. 2: Drainage density map; Fig. 3: Lineament density map

Moderate slopes ($5.8\text{--}10.1^\circ$) occur in scattered patches, while steep slopes ($>10^\circ$), represented by orange to red zones, are confined mainly to localized hilly tracts in the northern and central parts. These steep slopes accelerate runoff, limit infiltration, and are prone to soil erosion. The distribution pattern suggests that most of Ghatkesar is topographically suitable for recharge, while the steep upland pockets require soil and water conservation measures to minimize runoff losses. The slope map, therefore, provides an essential input for groundwater potential analysis, especially when integrated with drainage density, soil, and lineament density layers.



(4)



(5)

Fig. 4: Slope map; Fig. 5: Soil map

Soil map

Soil map of Ghatkesar Mandal shows a uniform distribution of loam-clay (Lc) soils across the study area. This soil type is characterized by moderate water-holding capacity, good nutrient retention, and relatively slow infiltration rates compared to sandy soils. The dominance of loam-clay soils have important hydrogeological implications: while these soils support agricultural productivity by conserving moisture, their reduced permeability restricts rapid infiltration and groundwater recharge.

Given the semi-arid climate of Ghatkesar, the presence of loam–clay soils enhance surface runoff during intense monsoon rainfall events, thereby contributing to higher drainage density in certain pockets. At the same time, sustained percolation through weathered rock layers allows for seasonal recharge of aquifers. Thus, while the soil regime is favourable for agriculture, it requires complementary soil and water conservation measures to optimize recharge potential. Integrating soil information with slope, lineament, and land use layers ensures a holistic understanding of groundwater dynamics in the Mandal.

Rainfall map

The spatial rainfall pattern over the Ghatkesar region was derived using ArcGIS geospatial interpolation of long-term precipitation records. The map (Figure 7) shows five rainfall classes ranging from approximately 1,035 mm to 1,065 mm, represented from light to dark blue. The north and south-western sectors of the study area receive comparatively higher rainfall (dark blue), while the eastern part records relatively lower values (light blue). This spatial variability indicates differences in potential recharge across the region.

Rainfall constitutes one of the primary factors controlling groundwater replenishment in hard-rock terrains. Incorporating the rainfall layer with other thematic inputs such as geology, soil, slope, drainage density and land use allows a weighted overlay analysis to delineate groundwater potential zones. Thus, the rainfall map presented here is a critical input in the assessment of groundwater potential zones for the Ghatkesar region using ArcGIS.

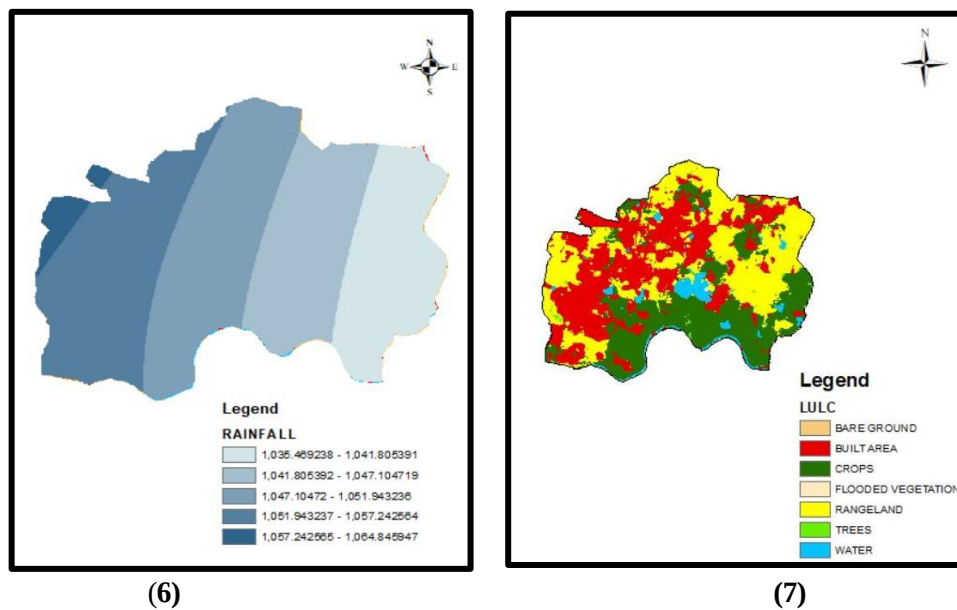


Fig. 6: Slope map; Fig. 7: Soil map

Land use/land cover

The land use/land cover (LULC) pattern of the Ghatkesar region was generated from recent satellite imagery using supervised classification in ArcGIS. Figure X depicts seven LULC categories – Bare Ground, Built-up Area, Crops, Flooded Vegetation, Rangeland, Trees, and Water – each represented by a distinct colour. Bare ground (beige) and rangeland (yellow) are widely distributed across the area, reflecting open land with sparse vegetation or fallow tracts. Built-up areas (red) occur in a dispersed pattern but are concentrated in the central and western parts, indicating settlements and infrastructure. Croplands (dark green) dominate the southern and central sectors, showing intensive agricultural use, while patches of flooded vegetation (pale yellow-green) mark low-lying or waterlogged areas. Tree cover (bright green) occurs mostly along drainage lines and undisturbed tracts, and water bodies (blue) are scattered in small ponds and tanks.

LULC mapping is a critical step in groundwater potential assessment because land cover strongly influences infiltration, runoff and recharge processes. Built-up surfaces and bare ground typically reduce infiltration, whereas croplands, trees and flooded vegetation promote higher infiltration and recharge potential. When combined with other thematic layers such as rainfall, slope, soil and drainage density, this LULC map provides a spatially explicit understanding of land–water interactions and serves as an essential input for the weighted overlay analysis to delineate groundwater potential zones in the Ghatkesar region.

Geology map

The geological layer of the study area was prepared from Survey of India and Geological Survey of India datasets and digitised in ArcGIS. As shown in Figure 9, the entire Ghatkesar region is underlain by the Peninsular Gneissic Complex–II (granite dominated), which appears as a uniform brown tone on the map. This formation represents ancient, highly crystalline basement rocks typical of the Deccan Shield. The dominance of granitic gneiss across the area indicates a hard-rock terrain with limited primary porosity but significant potential for secondary porosity through weathering and fracturing.

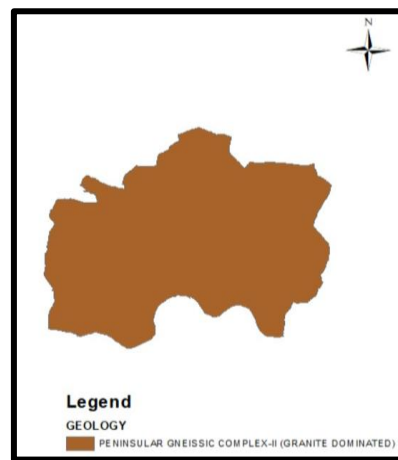


Fig. 8: Geology map

Geology exerts a fundamental control on groundwater occurrence in hard-rock regions. Granite-dominated gneisses have low infiltration and storage capacity in unweathered zones but can yield appreciable groundwater from weathered mantles and fracture networks. Therefore, identifying the spatial extent of this unit is critical for evaluating aquifer behaviour, recharge potential and well siting. The geology layer, combined with rainfall, slope, land use/land cover, soil and drainage density, forms an essential input to the weighted overlay analysis used to delineate groundwater potential zones in the Ghatkesar region.

Factors influencing ground water potential zones

The Groundwater occurrence in the Ghatkesar region is governed by a combination of hydrological, geological and geomorphological parameters. The drainage density of the area, derived from DEM using hydrology tools in ArcGIS, provides a measure of the total length of stream channels per unit area. High drainage density indicates less permeable rocks and greater surface runoff, whereas low drainage density indicates higher infiltration capacity and thus higher groundwater potential. Slope also plays a decisive role; steep slopes accelerate runoff and reduce recharge, while gentle undulating slopes provide more time for infiltration into underlying aquifers. In this study, slope was extracted from the DEM and categorised into nearly level, gentle, moderate and steep classes, with moderate slopes showing relatively better recharge potential.

Geology exerts a fundamental control on the storage and movement of groundwater. The Ghatkesar area is underlain mainly by granite belonging to the Peninsular Gneissic Complex. These hard rocks have very low primary porosity but can store groundwater in weathered mantles and fracture zones.

Soil properties further influence infiltration rates. Soils identified in the region range from loamy to clayey; loamy soils are more permeable and allow higher recharge, whereas clayey soils have lower permeability, reducing infiltration. Both geology and soil information were integrated into the model to reflect their effect on aquifer behaviour.

Lineaments and their density are another key factor in groundwater movement. Lineaments represent structurally controlled linear features such as faults and fractures that act as conduits for groundwater. In this study, lineament density was calculated on a 1 km × 1 km grid and grouped into five density classes. Zones of high lineament density were interpreted as more favourable for groundwater occurrence. Land use/land cover (LULC) also significantly affects infiltration and evapotranspiration. Built-up areas and bare ground tend to impede infiltration, whereas croplands, vegetation and water bodies promote recharge. A detailed LULC map was prepared from satellite data to capture these variations.

Rainfall, the primary source of recharge, was incorporated by preparing a rainfall distribution map using Indian Meteorological Department (IMD) gauge data. Because rainfall observations are point-based, the Inverse Distance Weighted (IDW) interpolation method was used to produce a continuous rainfall surface for the study area. This allowed a more representative estimate of spatial rainfall distribution, which, combined with topography and land use, indicates where rainfall is more likely to infiltrate rather than run off. Integrating all these thematic layers—drainage density, slope, geology, soil, lineaments, LULC and rainfall—provides a robust basis for delineating groundwater potential zones.

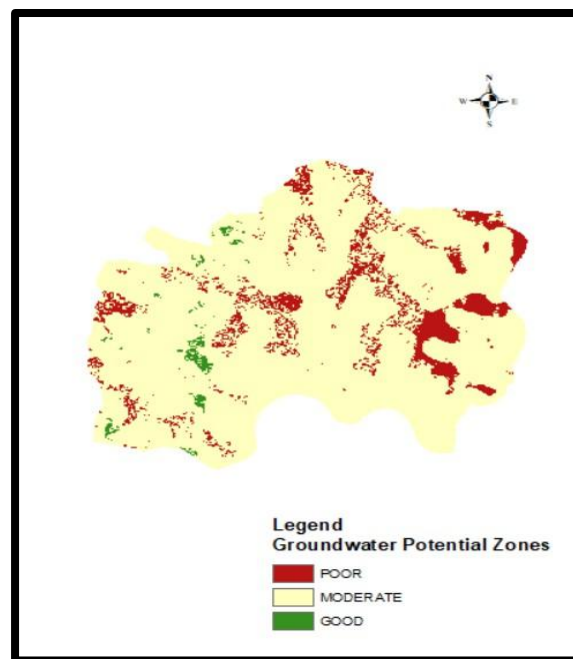


Fig. 9: Groundwater potential map

Figure 9 presents the spatial distribution of groundwater potential zones in the Ghatkesar region, delineated through a weighted overlay analysis of all thematic layers in ArcGIS. The area is classified into three categories: good (green), moderate (yellow) and poor (red) potential zones. Good potential zones correspond to areas with low drainage density, gentle slopes, permeable soils, high lineament density, favourable LULC and relatively high rainfall. Moderate zones represent transitional conditions, while poor zones coincide with steep slopes, compact rock, low lineament density and built-up surfaces.

The map clearly illustrates that only limited pockets of the study area fall into the “good” category, whereas large portions show moderate potential and scattered patches of poor potential. This spatial understanding of groundwater availability is crucial for planning groundwater extraction, artificial recharge and sustainable management strategies in the Ghatkesar region.

The final groundwater potential map delineates three categories:

- Good Potential Zones: valley fills, pediplains with dense lineaments, alluvial plains (~30% area).
- Moderate Potential Zones: weathered pediments, agricultural lands (~45% area).
- Poor Potential Zones: structural hills, residual uplands, and urban built-up (~25% area).

These findings indicate that artificial recharge structures such as percolation tanks, check dams, and recharge shafts are most suitable in moderate-to-poor potential zones, particularly where over-extraction has led to declining water tables.

Conclusion

The present study has successfully identified groundwater potential zones in Ghatkesar Mandal through the integration of multi-criteria thematic layers using ArcGIS. Parameters such as slope, drainage density, rainfall, lineament density, soil texture, geology and land use/land cover were analysed, reclassified and weighted to reflect their relative influence on recharge and storage. This approach provided a comprehensive understanding of the hydrogeological environment rather than relying on any single factor.

The resulting groundwater potential map delineates three distinct categories – low, moderate and high potential zones. High potential zones coincide with gently sloping terrain, low drainage density, permeable loamy soils, high lineament density and favourable land cover such as croplands and vegetated areas. Moderate zones represent transitional conditions with mixed characteristics, while low potential zones occur mainly in steep slopes, compact granite areas, dense built-up surfaces or soils with low permeability. This spatial pattern highlights the heterogeneous nature of groundwater occurrence in a hard-rock setting.

The map offers a practical tool for planners and water-resource managers to identify areas suitable for agricultural irrigation, drinking-water development and small-scale industrial use. It also indicates where artificial recharge structures such as check dams or percolation tanks would be most effective. By validating the results with available field data, the reliability and accuracy of the groundwater potential zones have been enhanced, making the findings robust for decision-making.

Overall, the study demonstrates the capability of geospatial techniques to integrate diverse datasets and produce scientifically sound outputs for sustainable groundwater management. The methodology developed here can be replicated in other regions with similar hydrogeological settings, thereby contributing to long-term water security and resource planning.

References

- Anbazhagan, S., & Jothibas, A. (2016). Remote sensing and GIS for groundwater potential mapping in hard rock terrain. *Arabian Journal of Geosciences*, 9, 367.
- Balamurugan, G., & Kumaraswamy, K. (2010). Groundwater exploration using remote sensing and GIS techniques in Tiruchirappalli District, Tamil Nadu. *International Journal of Geomatics and Geosciences*, 1(2), 223–234.
- Central Ground Water Board (CGWB). (2014). *Dynamic Ground Water Resources of India*. Ministry of Water Resources, Government of India.
- Central Ground Water Board (CGWB). (2012). *Groundwater Scenario in India 2012–13*. Ministry of Water Resources, Government of India.
- Chowdhury, A., Jha, M.K., & Chowdary, V.M. (2010). Delineation of groundwater recharge zones and identification of artificial recharge sites in West Medinipur district, West Bengal, India. *Environmental Earth Sciences*, 59(6), 1209–1222.
- Chowdhury, A., Jha, M.K., Chowdary, V.M., & Mal, B.C. (2009). Integrated remote sensing and GIS-based approach for assessing groundwater potential in West Medinipur district, India. *International Journal of Remote Sensing*, 30(1), 231–250.
- Dinesh Kumar, M. (2005). Impact of electricity prices and volumetric water allocation on energy and groundwater use efficiency in India. *Energy Policy*, 33(1), 39–51.
- Elango, L., & Kannan, R. (2007). Rock–water interaction and its control on groundwater quality in the

- lower Palar River basin, Tamil Nadu. *Environmental Geology*, 52, 563–574.
- Gupta, R.P., & Srivastava, P.R. (2010). Integrating GIS and remote sensing for groundwater recharge potential mapping in hard rock areas. *Hydrogeology Journal*, 18(7), 1713–1725.
- Jha, M.K., Chowdhury, A., Chowdary, V.M., & Peiffer, S. (2007). Groundwater management and development by integrated remote sensing and GIS: Prospects and constraints. *Water Resources Management*, 21(2), 427–467.
- Krishnamurthy, J., & Srinivas, G. (1995). Role of geological and geomorphological factors in groundwater exploration: A study using IRS LISS data. *International Journal of Remote Sensing*, 16(14), 2595–2618.
- Kumar, C.P. (2012). Climate change and its impact on groundwater resources. *Hydrology Journal of India*, 47(1), 1–12.
- Mondal, S., & Singh, R. (2011). Delineation of groundwater potential zones in hard rock terrain using geospatial techniques. *Geocarto International*, 26(3), 208–222.
- Murthy, K.S.R. (2000). Groundwater potential in a semi-arid region of Andhra Pradesh using GIS. *Journal of the Indian Society of Remote Sensing*, 28(4), 217–228.
- Nag, S.K. (2005). Application of lineament density and groundwater occurrence. *Journal of the Indian Society of Remote Sensing*, 33(4), 521–529.
- Pawar, N.J., & Devotta, S. (2000). Groundwater quality in hard rock areas: A case study from Maharashtra. *Current Science*, 79(8), 1038–1044.
- Rai, S.B., Tiwari, A.N., & Mohan, S. (2000). Remote sensing and GIS applications in groundwater hydrology. *Journal of the Geological Society of India*, 55, 135–142.
- Subba Rao, N. (2006). Seasonal variation of groundwater quality in a part of Guntur District, Andhra Pradesh. *Environmental Geology*, 49, 413–429.
- Srinivasa Rao, Y., & Jugran, D.K. (2003). Delineation of groundwater potential zones and identification of artificial recharge sites using remote sensing and GIS. *Hydrogeology Journal*, 11, 508–520.
- Rao, Y.R.S., & Briz-Kishore, B.H. (1991). Hydrogeomorphological and groundwater prospects of Vemulapally watershed through remote sensing. *Journal of the Indian Society of Remote Sensing*, 19(3), 171–180.
- Reddy, G.P.O., & Maji, A.K. (2003). Delineation and characterization of geomorphological features in a part of lower Maharashtra using IRS-LISS II data. *Journal of the Indian Society of Remote Sensing*, 31(4), 241–250.
- Saha, D., & Sinha, S.K. (2008). Hydrogeological framework and groundwater management strategies in the hard rock regions of India. *Journal of Geological Society of India*, 71, 615–629.
- Saraf, A.K., & Choudhury, P.R. (1997). Integrated remote sensing and GIS for groundwater exploration and identification of artificial recharge sites. *International Journal of Remote Sensing*, 18(9), 1825–1841.
- Sener, E., Davraz, A., & Ozcelik, M. (2005). An integration of GIS and remote sensing in groundwater investigations: A case study in Burdur, Turkey. *Hydrogeology Journal*, 13(5), 826–834.
- Singh, A., & Prakash, S.R. (2002). An integrated approach of remote sensing and GIS for groundwater mapping in hard rock terrain. In *Proceedings of ISRS Symposium* (pp. 67–72).
- Singh, P., Thakur, J.K., & Singh, U.C. (2013). Morphometric analysis of Morar River Basin, Madhya Pradesh, India, using remote sensing and GIS techniques. *Environmental Earth Sciences*, 68(7), 1967–1977.
- Todd, D.K., & Mays, L.W. (2005). *Groundwater Hydrology* (3rd ed.). John Wiley & Sons, New York.
- Tiwari, A.N., Rai, B., & Gupta, A. (2009). Application of remote sensing and GIS for delineation of groundwater potential zones in Jhansi district, Uttar Pradesh. *Journal of the Indian Society of Remote Sensing*, 37(2), 233–240.
- Vasanthavigar, M., Srinivasamoorthy, K., & Vijayaragavan, K. (2010). Application of water quality index for groundwater quality assessment: Thirumanimuttar sub-basin, Tamil Nadu, India. *Environmental Monitoring and Assessment*, 171, 595–609.
- Venkateswaran, S., & Elango, L. (2013). GIS-based groundwater potential mapping in parts of Tamil Nadu. *Journal of Earth System Science*, 122(4), 1125–1137.



Managing Groundwater for Sustainable Livelihoods: Insights from Chambal Ravines, Keshorai Patan Block, Bundi District, Rajasthan

Sayelli Tembhurne

Research Scholar, Department of Geology, Savitribai Phule Pune University, Pune, India.
Currently: Scientist, Central Ground Water Board, Central Region, Nagpur, India.
E-mail: tembhurnesayelli@gmail.com

Abstract

Ravine erosion is a critical environmental and socio-economic challenge in India, significantly reducing arable land and threatening rural livelihoods. The Chambal ravine zone, known for its deeply incised and intricate gully networks, has witnessed extensive land degradation, particularly in the Keshorai Patan Block of Bundi District, Rajasthan. Gully formation along the Chambal River—driven by rainfall, surface runoff, and human activities—has led to a decline in agricultural productivity, forcing a shift in livelihood patterns from traditional farming to animal husbandry and urban migration. This study analyzes the hydrogeological, geomorphological, and drainage characteristics of the Chambal ravines to assess their impact on groundwater resources and socio-economic conditions. Using spatial analysis and field-based observations, the research examines the interconnections between land degradation, groundwater availability, and livelihood adaptation. The study further proposes sustainable management strategies, including soil conservation, afforestation, rainwater harvesting, and controlled land use, to mitigate erosion and enhance agricultural resilience. By integrating scientific assessment with practical management approaches, this research aims to provide valuable insights for policymakers, environmental planners, and local stakeholders, ensuring sustainable groundwater and livelihood management in semi-arid ravine-affected regions.

Keywords: Ravines, Groundwater management, Sustainable livelihood, Rajasthan

1. Introduction

Soil erosion is a critical environmental issue contributing to extensive land degradation worldwide. Among the various forms of erosion, gully and ravine formation represent the most severe and irreversible processes, leading to significant loss of fertile land, reduced agricultural productivity, and long-term socio-economic challenges. In India, ravines are widespread along major river systems, occupying nearly four million hectares—approximately 1% of the country's total land area (Ministry of Agriculture, 1984). The most severely affected regions include the Yamuna-Chambal Ravine Zone, the Gujarat Ravine Zone (Tapti-Narmada-Sabarmati-Mahi), the Chhota Nagpur Ravine Zone, and the Siwalik Foothills Ravine Zone (Sharma, 1980). Of these, the largest and most intensively degraded is the Yamuna-Chambal Ravine Zone.

The Chambal Ravines flank the Chambal River for approximately 480 km in a belt nearly 10 km wide, occupying about 0.5 million hectares of land (Haigh, 1984). These ravines are highly incised, reaching depths of 60–80 meters, and present serious challenges to land-use planning, agricultural development, and environmental sustainability (Sharma, 1968, 1979; Haigh, 1984; Larue, 2005). The process of ravine formation in this region is primarily driven by hydrological and geomorphic factors, including intense rainfall, surface runoff, and gully expansion. Additionally, anthropogenic activities such as

deforestation, overgrazing, and unsustainable land use have further accelerated soil erosion and land degradation.

Remote sensing techniques have played a crucial role in mapping and classifying ravines in the Chambal region. Optical multi-spectral and high-resolution panchromatic images have been widely used for qualitative classification based on depth and erosion patterns (Singh et al., 1998; Sujatha et al., 2000; Dwivedi and Ramana, 2003). However, despite advancements in remote sensing and land-use studies, effective management strategies and sustainable livelihood remain a challenge, particularly in balancing ecological restoration with socio-economic development.

In the Keshorai Patan Block of Bundi District, Rajasthan, ravine formation along the Chambal River has drastically impacted groundwater availability and agricultural livelihoods. The progressive loss of cultivable land has forced local communities to shift from crop-based farming to animal husbandry, while others have been compelled to migrate due to declining economic opportunities. Vegetation loss, declining soil fertility, and reduced groundwater recharge further exacerbate food and water insecurity in the region.

This study aims to assess the impact of ravine erosion on groundwater resources and livelihood patterns using a combination of hydrogeological, geomorphological, and spatial analysis approaches. By integrating field observations with remote sensing data, the research seeks to develop a sustainable management framework for mitigating ravine expansion, restoring degraded lands, and enhancing groundwater utilization. The findings will contribute to the formulation of effective land and water conservation strategies, providing valuable insights for policymakers, environmental planners, and local communities in ravine-affected semi-arid regions.

2. Materials and Methods

2.1 Location & extent

The study area is a part of the Chambal River basin, the Keshorai Patan Block of Bundi District, Rajasthan (Fig. 1). It covers approximately 1,243 km² in the south-eastern region of the district, extending between 25°51' to 25°13' N latitude and 76°21' to 75°51' E longitude. Keshorai Patan Block is classified as an semi-critical groundwater zone, experiencing significant water stress, with a groundwater development stage of 73.23% as per ground water resource estimation 2020. Of the total area, 1,152 km² is identified as a potential recharge-worthy zone, highlighting the urgent need for sustainable groundwater management and conservation measures.

2.2 Rainfall

Keshorai Patan Block receives relatively higher rainfall compared to other districts of Rajasthan, with an average annual precipitation of 687 mm (1984–2020). Despite this, the region experiences a predominantly dry yet healthful climate. The year is divided into four distinct seasons: the hot summer from March to mid-June, characterized by intense heat and arid conditions; the monsoon season from mid-June to September, during which the southwest monsoon brings 93% of the total annual rainfall, playing a crucial role in groundwater recharge and surface water availability; the post-monsoon season from October to November, marked by a gradual decline in temperature and receding rainfall; and the cold winter season from December to February, which is relatively dry with cool temperatures. In certain years, rainfall has exceeded the long-term average, leading to instances of flooding in major parts of the block, which in turn accelerates soil erosion, land degradation, and challenges in water resource management.

2.3 Geomorphology

The landscape of Keshorai Patan Block is defined by a diverse geomorphological framework, including dissected plateaus, valley fills, buried piedmont, alluvial plains, and ravines. Ravines, a characteristic feature of the Chambal badland topography, dominate a significant portion of the block, shaping its terrain and influencing land use patterns. The geomorphological map of Keshorai Patan Block (Fig. 2)

illustrates the spatial distribution of these landforms. Notably, ravines and alluvial plains occupy the majority of the area along the rivers in the southeastern part of the block, highlighting the impact of fluvial processes in shaping the region's landscape.

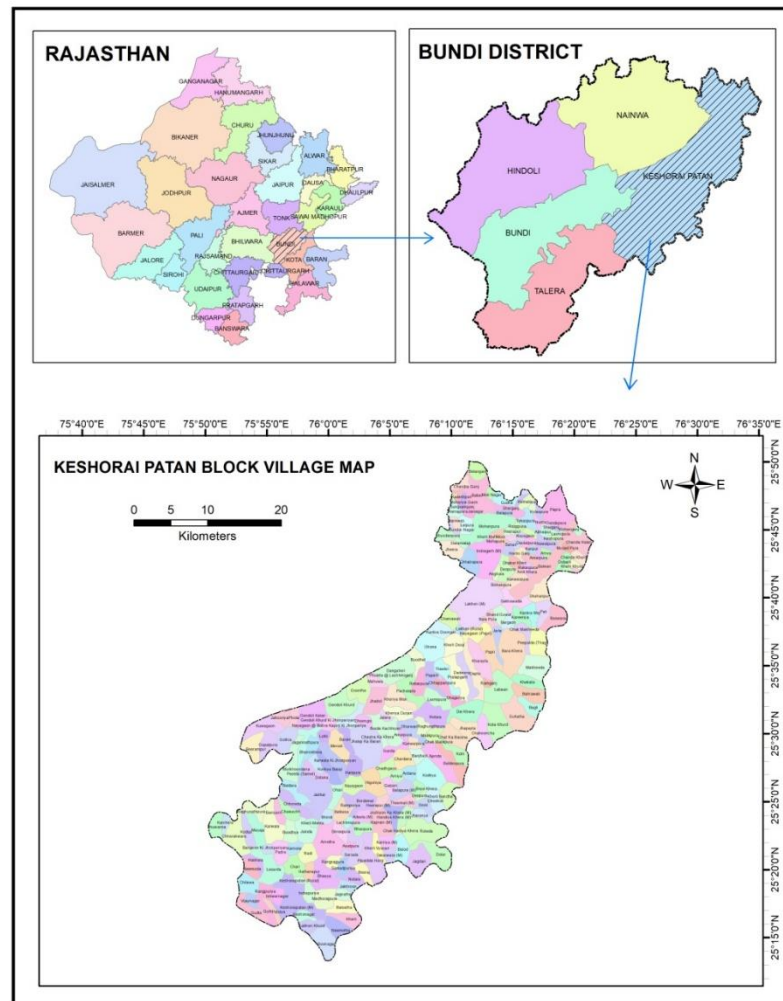


Fig.1 Location map of Keshorai patan Block, Bundi District.

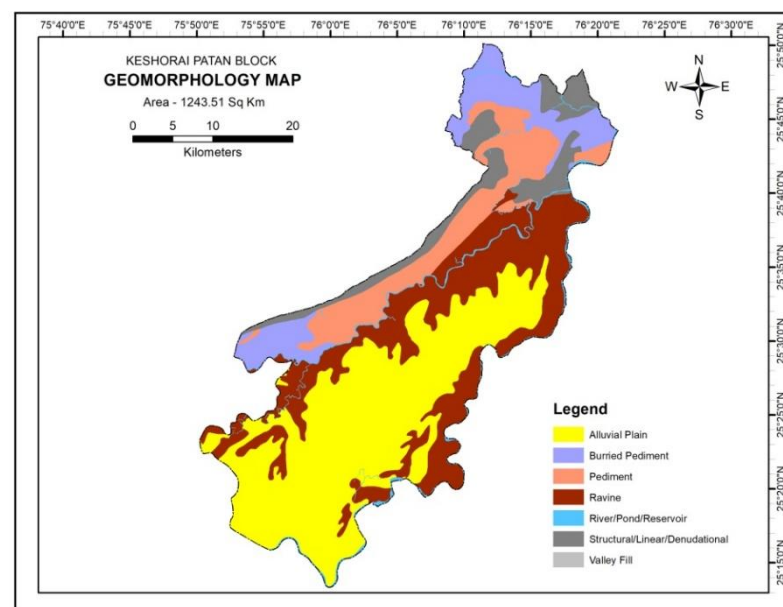


Fig.2: Geomorphology of Keshorai patan Block.

3. Result and Discussion

3.1 General Hydrogeology

Geologically, Keshorai Patan Block is primarily composed of alluvium and shale, with occurrences of sandstone, limestone, and phyllite. The groundwater in the region predominantly exists under unconfined conditions, stored within pore spaces in alluvial deposits and fractures developed in hard rock formations due to primary and secondary porosity. These geological characteristics significantly influence groundwater availability and movement within the area. The geological framework of the block is depicted in Figure 3. Additionally hydrograph of monsoon & annual rainfall (mm) versus pre & post monsoon water level (m,bgl) for the period from 2005 to 2016 is depicted in Figure 4. Also, Ground water salinity more than 3000ms/cm at 25oC has been observed mainly in Southeastern part of Keshorai Patan block.

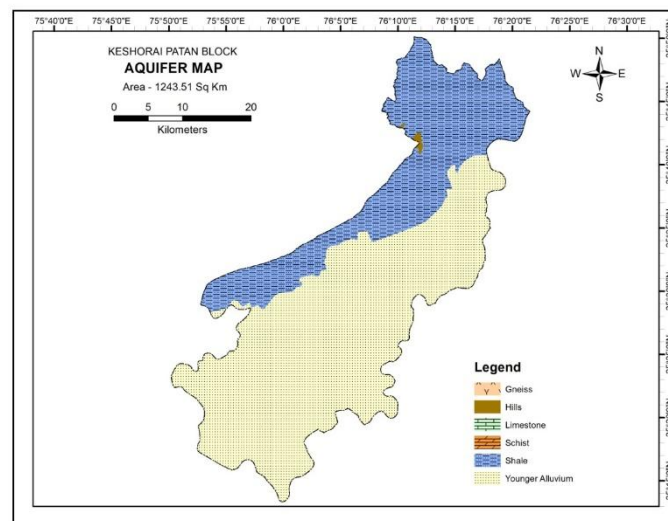


Fig.3 Aquifer map of Keshorai patan Block.

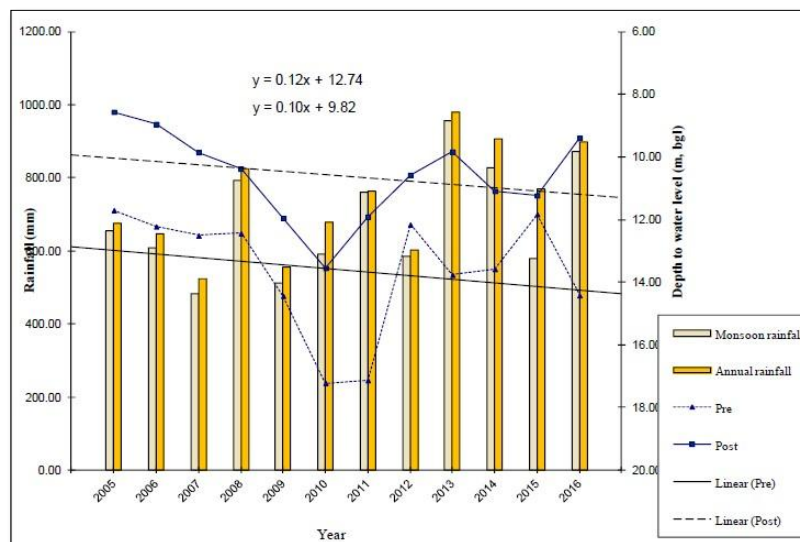


Fig. 4 hydrograph of monsoon & annual rainfall (mm) versus pre & post monsoon water level (m,bgl) for the period from 2005 to 2016 of Keshorai Patan block, Bundi district.

3.2 Groundwater Scenario – Pre-Monsoon (May 2020)

During the pre-monsoon period (May 2020), the depth to the water level in Keshorai Patan Block varied significantly, ranging from 2 meters below ground level (m bgl) to 40 m bgl (Figure 5). The depth to water level map reveals a distinct spatial variation across the block. The southwestern region

predominantly exhibits shallower water levels, ranging between 2 and 10 m bgl, indicating relatively higher groundwater availability. In contrast, the northeastern region generally records deeper water levels, varying between 10 and 20 m bgl, with isolated patches where water levels reach depths of 20 to 40 m bgl. These variations reflect the influence of geological formations, topography, and recharge conditions on groundwater distribution in the region.

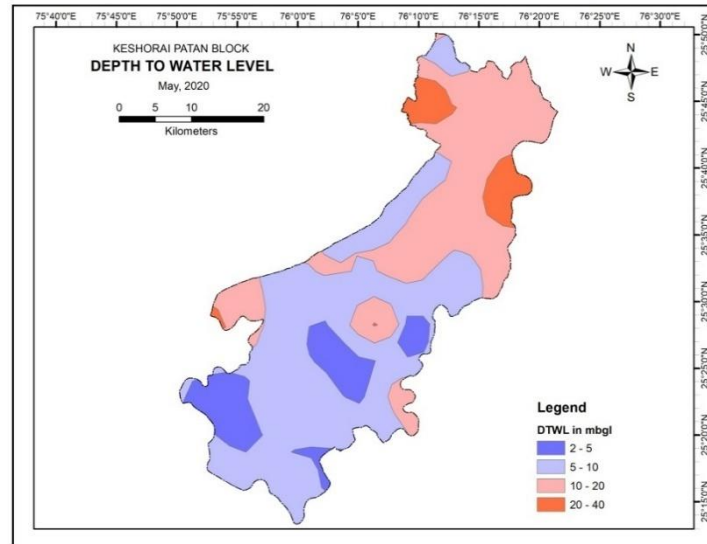


Fig.5 Depth to water Level Map Pre-Monsoon 2020, Keshorai patan Block.

3.3 Groundwater Scenario – Post-Monsoon (November 2020)

During the post-monsoon period of November 2020, the depth to the water level in Keshorai Patan Block ranged from approximately 2 to 20 meters below ground level (m bgl), reflecting the recharge effect of seasonal rainfall. The post-monsoon depth to water level map (Figure 6) highlights a significant improvement in groundwater levels compared to the pre-monsoon period. A large portion of the block exhibits water levels between 2 and 10 m bgl, indicating widespread replenishment. However, a distinct patch in the eastern region shows deeper water levels between 10 and 20 m bgl, which may be attributed to the base flow of groundwater towards the Chambal River, influencing localized groundwater availability and movement.

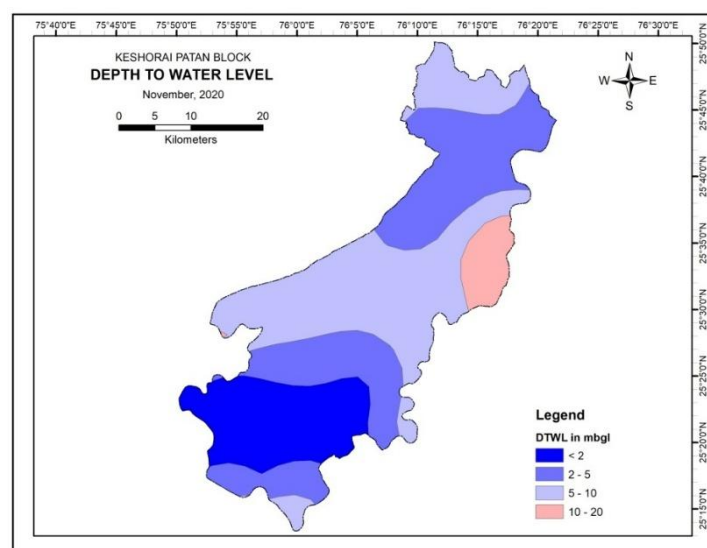


Fig.6 Depth to water Level Map Post-Monsoon 2020, Keshorai patan Block.

3.4 Dynamic Groundwater Resources, 2020

The groundwater resource status of Keshorai Patan Block is detailed in Table 1, highlighting the current availability and usage trends. The annual net groundwater availability in the block is estimated at 7,747 ham, while the annual gross groundwater draft for all uses stands at 5,674 ham. This indicates a groundwater development stage of 73%, signifying a substantial level of extraction relative to recharge. Such a utilization rate places the region under moderate to high groundwater stress, necessitating sustainable management strategies to prevent overexploitation and ensure long-term water security.

Table 1: Ground Water Resources (As on 31.3.2020)

Annual Extractable Ground water Resource (MCM)	77.47
Existing Gross Ground Water Draft for All uses(MCM)	56.74
Net Annual Ground Water Availability for Future Use (MCM)	20.73
Stage of Ground Water Development %	73%
Source: Ground Water Resource Assessment 31.03.2020	

Table 2: Comparison of GWRA 2020 with that GWRA 2017

	2020	2017
Total Annual Ground Water Recharge (ham)	8608.71	16343.06
Annual Extractable Ground water Resource (ham)	7747	14708.75
Domestic Draft (ham)	651.62	607.65
Industrial Draft (ham)	0	0
Irrigation Draft (ham)	5022.79	9596.09
Existing Gross Ground Water Draft for All uses(ham)	5674.00	10203.74
Net Annual Ground Water Availability for Future Use (ham)	2073.43	4991.43
Stage of Ground Water Development %	73.230	69.37
Category	semi critical	safe

3.5 Management Interventions

Groundwater plays a crucial role in sustaining livelihoods, particularly in the semi-arid regions of Rajasthan, where surface water availability is limited. Regardless of the stage of economic development, groundwater remains an indispensable resource for agriculture, drinking water, and industrial use. However, intensive groundwater extraction over the past few decades has led to a steady decline in water levels and diminishing groundwater reserves, posing a significant challenge to long-term water security. To address this issue, a comprehensive groundwater management plan has been proposed, integrating both supply-side and demand-side management strategies.

Supply Side Management

Supply-side management is aimed at enhancing groundwater availability through scientifically planned interventions, considering environmental, social, and economic factors. This approach includes structural measures such as artificial recharge and rainwater harvesting to replenish groundwater reserves. By conserving surface water and utilizing surplus rainfall runoff within river sub-basins and micro-watersheds, groundwater storage can be effectively augmented. A ridge-to-valley approach is implemented, where water conservation structures are strategically placed along stream networks, beginning with small second-order streamlets and gradually extending to larger streams as per feasibility. Additionally, understanding the de-saturated aquifer volume is crucial to ensure effective recharge and prevent over extraction. Implementing these measures not only helps in sustaining groundwater levels but also supports agricultural activities, drinking water supply, and overall ecological balance. The drainage map of the block (Figure 7) provides insights into the region's hydrological network, aiding in the planning and execution of these conservation strategies.

The de-saturated aquifer volume for Bundi block has been calculated based on three key parameters: the area suitable for recharge, unsaturated depth exceeding 6 m bgl, and the specific yield of the aquifer. This estimation helps in determining the groundwater recharge potential and planning appropriate

measures for sustainable water management. The volume available for recharge in the block is detailed in Table 3, while Table 4 outlines the suitable artificial recharge structures based on groundwater availability. Additionally, Table 5 provides a cost estimation for implementing these recharge structures, ensuring an efficient and economically viable groundwater management plan. Area identified for artificial recharge i.e. area with water level more than 3m bgl depth to water level is depicted in figure 8.

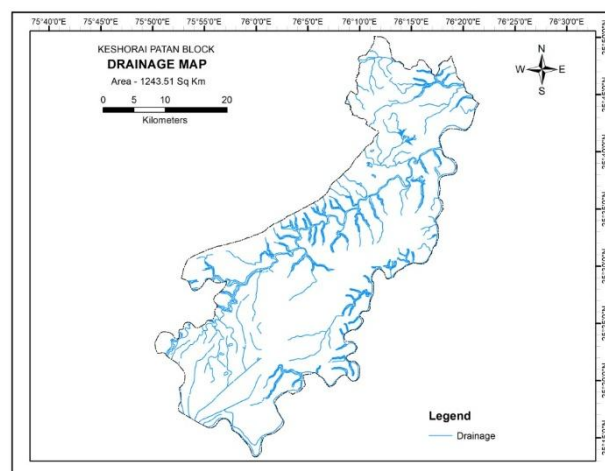


Fig. 7 Drainage Map of Bundi Block.

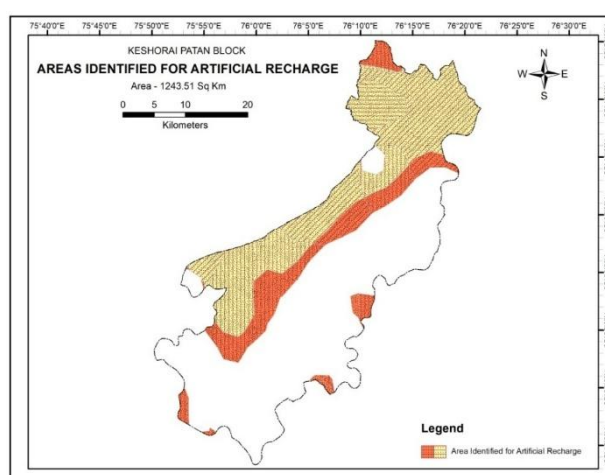


Fig. 8 Area Identified for Artificial Recharge

Table 3: Volume of sub surface space available for artificial recharge

Total Geographical Area (sq.km)	Potential area (sq.km)	Type of aquifer	Volume of sub surface space available for artificial recharge (mcm)	Surplus surface water available in (MCM)
1243.51	1152.88	Schist	80.62	174

Table 4: Types of artificial recharge structures as per groundwater availability. Source: Master plan 2020, Bundi District, Rajasthan.

Block	Mini Percolation Tank	Percolation Tank	Pacca Check dam	Anicut	Mini Storage Tank	Surplus water Utilized by (MPT/PT/P CD/ Anicut/MS T) (mcm)	Surplus water available for Farm Pond (mcm)	No. of Recharge/ Farm Pond (One farm pond in 3 ha land proposed in 25% of arable land)	Surplus water utilized by Farm Pond (mcm)
Bundi	1557	685	352	207	12	5.19	168	676	0.81

Table 5: Cost Estimate of Artificial Recharge Structures. Source: Master plan 2020, Bundi District, Rajasthan.

Average cost (Rs) of Catchment area treatment/ha	Average cost (Rs) of Mini Percolation tank (1000 cu m)	Average cost (Rs) of Percolation tank (2000 cu m)	Average cost (Rs) of Pacca Check Dam (4000 cu m)	Average cost (Rs) of Ani-cut (6000 cu m)	Average cost (Rs) of MST (9000 cu m)	Total cost (Rs in crore) of (MPT/PT/PCD/Anicut/MST)	Average cost (Rs) of Farm Pond of 1200 cum capacity	Total cost (Rs in crore) of Farm pond
100000	100000	300000	600000	1500000	5000000	94.29	150000	10.14

Demand Side Management

Effective groundwater resource management not only requires scientific development of available resources but also emphasizes their judicious and sustainable utilization. Key aspects of demand-side management include ownership of groundwater, need-based allocation and pricing, stakeholder participation in planning and monitoring, and implementation of regulatory measures where necessary. One of the most impactful measures is the adoption of micro-irrigation techniques, such as sprinkler systems, which can significantly reduce groundwater withdrawal. If 50% of the irrigation area currently dependent on groundwater adopts sprinkler irrigation, it can result in a water saving of 4.87 MCM. However, in Keshorai Patan Block, micro-irrigation alone will not be sufficient to ensure groundwater sustainability. Therefore, a cropping pattern shift is necessary, particularly replacing wheat cultivation with gram in 50% of the area, which can further conserve 26.17 MCM of water. By implementing these interventions (supply and demand), the current groundwater extraction level is expected to reduce from 73% to 30%, ensuring long-term sustainability of water resources.

4. Conclusion and Recommendation

Over the past few decades, rapid groundwater development has significantly contributed to rural livelihoods, providing drought-resilient, low-cost, and high-quality water supplies for both domestic and agricultural use. However, unregulated extraction and limited investment in resource management have led to declining water levels, increased soil erosion, and reduced agricultural productivity. Groundwater sustainability is not just a hydrogeological concern but is deeply intertwined with land-use policies, surface water management, and socio-economic conditions. Given the complex and variable nature of groundwater systems, a one-size-fits-all solution is not feasible. Therefore, an integrated groundwater management plan is essential for ensuring long-term water security and sustainable livelihoods.

The assessment of groundwater resources in Keshorai Patan Block indicates a concerning trend. The block's groundwater development stage increased from 69% (2017) to 73% (2020), shifting its classification from "Safe" to "Semi-Critical". This alarming shift necessitates immediate water conservation and artificial recharge interventions. Analysis of groundwater extraction trends reveals a significant increase in total water usage, particularly for irrigation, further stressing the available resources.

Ravine expansion into inland areas poses a significant environmental and socio-economic challenge in Keshorai Patan Block. The unchecked lateral and headward erosion of ravines not only reduces arable land but also threatens settlements, infrastructure, and groundwater recharge zones. As these deep

incisions continue to extend further into fertile lands, they accelerate soil erosion, land degradation, and loss of agricultural productivity, ultimately affecting the livelihoods of local communities. The fragile nature of the Chambal badland topography, coupled with deforestation, overgrazing, and unsustainable land-use practices, has exacerbated this issue, making it imperative to implement effective ravine control and reclamation strategies.

Field photographs (Figure 9 and 10) of the Chambal ravines in the study area vividly depict the extent of land degradation and the loss of agricultural land due to severe erosion. These images highlight the advancing ravine formations, emphasizing the urgent need for soil conservation and land reclamation measures. Additionally, photographs documenting Information, Education, and Communication (IEC) activities conducted in the study area showcase community engagement efforts aimed at promoting awareness, capacity building, and sustainable groundwater management practices. These initiatives play a crucial role in fostering local participation and ensuring the successful implementation of conservation strategies.



Fig. 9. Some field photographs of the Chambal ravines showing lost agricultural land in study area.



Fig. 10. Some field photographs of the Information, Education, and Communication (IEC activity) in study area.

- To improve groundwater availability, various structural interventions have been proposed, Catchment area treatment and water conservation structures, including percolation tanks, check dams, farm ponds, and anicuts, to enhance infiltration and reduce runoff. Earthen dams in ravine zones to increase well sustainability and groundwater recharge. Artificial recharge measures targeting unsaturated aquifers, ensuring sustainable groundwater replenishment.
- Demand-Side Management (Reducing Water Use & Improving Efficiency), Given the high dependence on groundwater for irrigation, demand-side measures focus on efficient water use and sustainable cropping patterns, Adoption of micro-irrigation techniques (drip and sprinkler systems) to optimize water use and reduce agricultural water withdrawals. Implementing sprinklers on just

50% of groundwater-irrigated land can save 4.87 MCM of water. Roof-top rainwater harvesting initiatives—encouraging households and communities to harvest rainwater, reducing stress on the water supply system.

- Crop diversification and modification—shifting 50% of wheat cultivation to gram can save 26.17 MCM of water, reducing overall demand. Promoting integrated farming systems, including horticulture, agroforestry, and fodder crops, to reduce reliance on water-intensive agriculture. Community-based farm ponds—constructing farm ponds in regions with deep water levels to store post-monsoon runoff for dry-season irrigation.
- Land leveling and lift irrigation projects in ravine-affected areas, utilizing government schemes such as MGNREGA for implementation.
- Limiting extensive groundwater withdrawal by regulating agricultural electricity subsidies, encouraging farmers to adopt more sustainable irrigation practices. Groundwater ownership and regulation—developing policies for need-based allocation and pricing mechanisms to prevent over-extraction.
- Community Involvement and Policy Interventions, A successful groundwater management plan requires active community participation, policy support, and institutional coordination.
- Integrated waste-water recycling and reuse—treating and reusing at least 50% of extracted groundwater for non-drinking purposes such as irrigation, toilet flushing, and industrial use.
- Institutional collaboration—strengthening partnerships with PHED, Water Resources Department, Forest Department, Agriculture Department, KVKs (Krishi Vigyan Kendras), Panchayats, and NGOs for effective groundwater governance.
- Implementation of these interventions will reduce groundwater extraction from 73% to 30%, ensuring long-term sustainability of groundwater resources. Additionally, ravine reclamation and watershed management will help mitigate land degradation, improve soil moisture retention, and enhance agricultural productivity in the region.

The dynamic interplay between groundwater sustainability and ravine expansion in Keshorai Patan Block necessitates a holistic and proactive approach to resource management. Without immediate intervention, land degradation and groundwater depletion will continue to intensify, jeopardizing agricultural productivity, water security, and rural livelihoods. A multi-sectoral strategy, incorporating scientific, ecological, and socio-economic considerations, is essential to curb ravine encroachment and ensure sustainable groundwater utilization.

Mitigating ravine expansion requires a combination of mechanical, biological, and community-driven approaches. Measures such as contour trenching, check dams, gully plugging, and afforestation can stabilize slopes and reduce soil erosion. The integration of agroforestry, grassland development, and controlled grazing can further enhance land resilience. Additionally, constructing earthen dams and percolation tanks within ravine-affected areas can improve groundwater recharge and mitigate further landscape degradation. Land leveling and lift irrigation can be implemented to reclaim land for agriculture, ensuring economic viability for local communities. By integrating advanced water conservation techniques, community participation, afforestation efforts, and policy-driven interventions, the region can transition towards a resilient and adaptive landscape. The collaboration of government bodies, scientific institutions, and local communities will be instrumental in restoring ecological balance, enhancing groundwater recharge, and securing the future of this vulnerable yet resource-rich landscape.

Acknowledgements

The author is grateful to Dr. P. Madhnure, Regional Director, Central groundwater Board, Nagpur, India, and Dr. S. J. Sangode, Head of Department, Pune University, Pune for their kind support and encouragement.

Reference

- Dwivedi, R.S., Ramana, K.V., 2003. The delineation of reclamative groups of ravines in the Indo-Gangetic alluvial plains using IRS-1D LISS-III data. *International Journal of Remote Sensing* 24 (22), 4347_4355.
- Haigh, M.J., 1984. Ravine erosion and reclamation in India. *Geoforum* 15 (4), 542_561.
- Larue, J.P., 2005. The status of ravine-like incisions in the dry valleys of the Pays de Thelle (Paris Basin, France). *Geomorphology* 68 (2), 242_256.
- Ministry of Agriculture, 1984. Report of the Working Group on Reclamation and Development of Ravines for formulation of the Five-Year Plan, Government of India. Ministry of Rural Development, Department of Land Resources, New Delhi, India.
- Ministry of Jal Shakti, 2022. Report on Aquifer mapping and groundwater management of Bundi District, Rajasthan.
- Sharma, H.S., 1968. Genesis and pattern of ravines of the Lower Chambal Valley, India. 21st International Geographical Union Congress 30 (4), 14_24 (special issue).
- Sharma, H.S., 1979. The physiography of the Lower Chambal Valley and its Agricultural Development: A Study in Applied Geomorphology, first ed. Concept Publishing Company, New Delhi.
- Sharma, H.S., 1980. Ravine Erosion in India, first ed. Concept Publishing Company, New Delhi.
- Sujatha, G., Dwivedi, R.S., Sreenivas, K., Venkataratnam, L., 2000. Mapping and monitoring of degraded lands in part of Jaunpur district of Uttarpradesh using temporal spaceborne multispectral data. *International Journal of Remote Sensing* 21 (2), 519_531.



Ground Water Studies of Upper Indravati Irrigation Project, Odisha

S. K. Sharma^{1,2}, Lalit Gupta²

1. WAPCOS Limited
2. Central Ground Water Board (CGWB), Ministry of Jal Shakti, Government of India
E-mail: sksharma1942@gmail.com

Abstract

Ground water availability and balance including long-term ground water level trends for composite Upper Indravati Irrigation Project (UIIP) command in kalahandi district of Odisha state for pre and post-project periods and for composite project area (drought prone area) are assessed. Largest Rain-fed area belongs to Right Extension Canal (REC, Bawanipanta block) and largest irrigated area (Junagadh block) belongs to Right Main canal (RMC). Annual replenishable ground water in blocks covering Irrigation commands is of sizeable magnitude. Quantum of ground water for conjunctive use in UIIP command is assessed. Water balance is strongly affected by agricultural practices and ground water recharge mainly originating from irrigation losses. The watershed measures (check dams & weirs) in local streams and in adjoining Hati-watershed area of command offer good scope for arresting & conserving run-off. Right main Canal (Junagadh & Kalampur blocks) have significant ground water balance potential and the same is true for Left Extension Canal System area.

1. Introduction

The project study area is depicted in Index map of Indravati River system (Fig.1). The study of ground water scenario was taken-up adjoining the Reservoir and canal command areas of project which was completed in year 1999. The Irrigation Canal Network systems are Right Main Canal (RMC) system, Left Main Canal (LMC) system, and their extension systems as well as lift Canal System. The canals, minors, ground water bore wells were inspected during the study. Interactions /discussions were held with farmers/representatives of Water user associations (WUAs) and state govt. officials.

The paper describes the Hydrogeological & Ground water status of Upper Indravati Irrigation Command of Kalahandi district (a drought prone area) of Odisha State. The study included Spatio-temporal Groundwater Level trend-analysis of Canal-commands. Also, the irrigation potential created in Kalahandi district (pre-project period, 2015) are described including the assessment of future period irrigation coverage areas in canal irrigation commands. The status of ground water availability, draft and gaps as well as scope for ground water based management in various canal command segments of UIIP are outlined.

2. Objective of Study

An Irrigation system is a hydraulic system designed to transport water from a Dam or River as a source to various users:

- i. The aim of Project scheme is to deliver water at right time in proper amount while minimizing losses and ensuring safety & guarantee of infrastructure. A major concern is to prevent canals from over-topping.

- ii. Spatial & temporal assessment of ground water use, availability of surface water supplies & climate data are used to assess quantity & quality of groundwater resources. The major components of water balance are recharge from rainfall, river & canal leakages and irrigation.
- iii. The ultimate objective of the study is to optimize ground water management to assist water-user associations in maximising crop production.

3. Physical Setting

The topographic, climate & rainfall as well as severity of drought in Command area is considered:

3.1. Topography & Drainage

The Project area generally slopes northwards. The rivers also drain northward except Tel river which flows eastwards. The rivers and canal systems are depicted in Index Map (fig. 1) of Upper Indravati (Odisha).

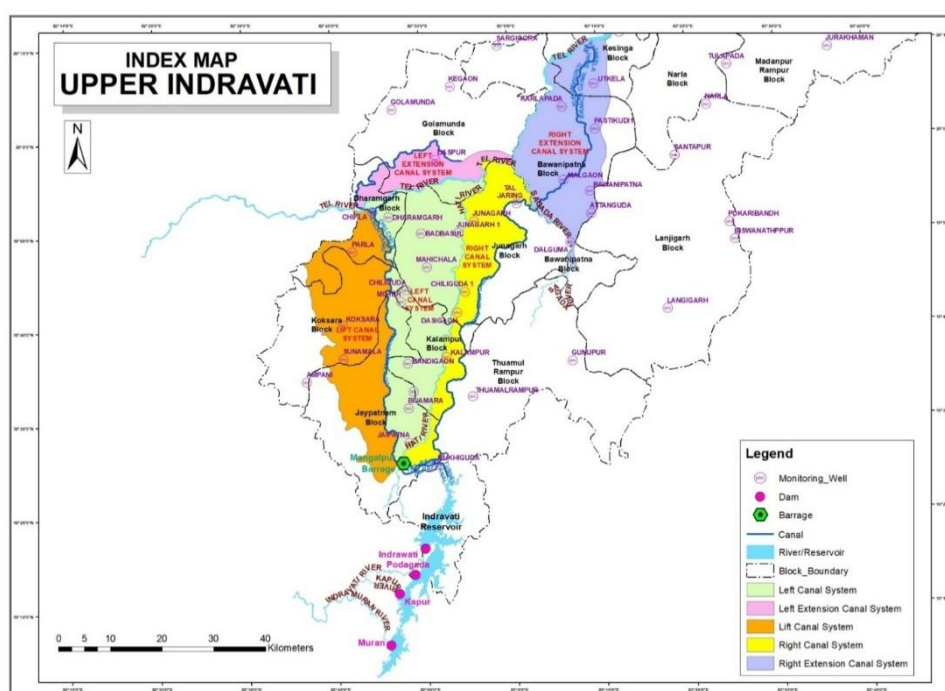


Figure 5: Index Map of Upper Indravati

3.2. Climate & rainfall

The average annual rainfall in project area is 1431 mm. and normal rainfall as 1376 mm. The rainfall in project area and for the period of study is given in Table-1 below:

Table 1: Rainfall in Project Area

YEAR	NORMAL RAINFALL (mm)	ACTIVE RAINFALL (mm)	DEVIATION FROM NORMAL RAINFALL		NATURAL CALAMITIES
			(mm)	(%)	
1980	1502.5	1321.7	-180.8	-12.03	Flood, Drought
1987	1502.5	1040.8	-461.7	-30.73	Severe Drought
1995	1502.5	1726.9	224.4	14.94	Drought
2000	1482.2	1034	-448.2	-31.18	Drought
2006	1482.2	3203.8	1721.6	116.15	Flood
2014	1482.2	1276.87	-205.32	-13.85	

3.3. Frequency & Severity of Drought in Command Area

It is outlined in Table-2 below.

Table 2: Frequency & Severity of Drought in Command Area

S. No.	Block	No. of years of drought	Drought frequency	Normal drought	Severe Drought
a.	Bhawanipatna	6	1 in 6 years	6	1
b.	Kasinga	-	1 in 20 years	-	2
c.	Kalanpur	2	1 in 10 years	2	1
d.	Golmunda	1	1 in 10 years	1	-
e.	Koksara	1	1 in 6 years	1	-
f.	Junagadh	1	1 in 10 years	5	1
g.	Jaypatna	3	1 in 2 years	3	-

4. Hydrogeomorphological & Groundwater Status of UIIP Project, Odisha

It is as mentioned below:

4.1. Hydro-geomorphological Set-up

These include;

- Geomorphology: The area comprises rugged hill ranges, undulating plains, residual hills and valleys. The Kokasara-Junagarh tract have elevation from 220 to 325m (amsl). The elevation in Utkela-Kesinga tract is 186m to 35m(amsl)
- Soil Types: Black soil with clay occupies part of areas in Bhawanipatna, Kesinga, Dharamgarh, Golmunda, and Kokasra blocks. Red soils occupy foot-hill region.
- Hydrogeology: Granites and gneisses having weathered zones and underlying fractured zones are principal water-bearing aquifers. Usually 2 to 4 water bearing fracture zones occur down to 110m depth in the area. Weathered zones upto 15m depth yield 2-3 lps through dug wells. Borewells from 60 to 200m depth yield between 3 & 19 liters per second.
- Hydrogeological map of Area: Its placed at fig.2
- Groundwater Status & Resources: The post-monsoon DTW level map is at fig. 3. The general ground water flow is towards north as well as towards east in the project area.
- Groundwater Thresholds of Project Area: These are as given in table-3 below.

Table 3: Ground Water Thresholds of Project Area

S. No.	Aquifer Characters	Values
1	Aquifer attribute	Granitic gneiss, Khandolite and Alluvium
2	Aquifer size	4 to 5 fracture zones occurring in hard rock aquifer to a depth of 100m and occasionally up to 194m depth(Narla block)
3	Aquifer hydraulic conductivity	T=4 to 20 m ² /day S= 1.3x10 ⁻⁴ to 4.3*10 ⁻⁴
4	Aquifer Well Yield	Hard rocks “ 1 to 18 liters per seconds (lps) Alluvial aquifer “5 to 10 “ (lps) by shallow tube wells
5	Ground water quality	EC of shallow aquifer: 110 to 4805 micromhos; TH= 40 to 2130 mg/l
6	DTW/Pz level	Pre-monsoon level: 1.3-9.4m(bgl); Post-monsoon level:0.84-4.47m(bgl)

S. No.	Aquifer Characters	Values
7	Hydrologic connectivity between surface and ground water	Exists locally in valley areas
8	Recharge Potential	Moderate

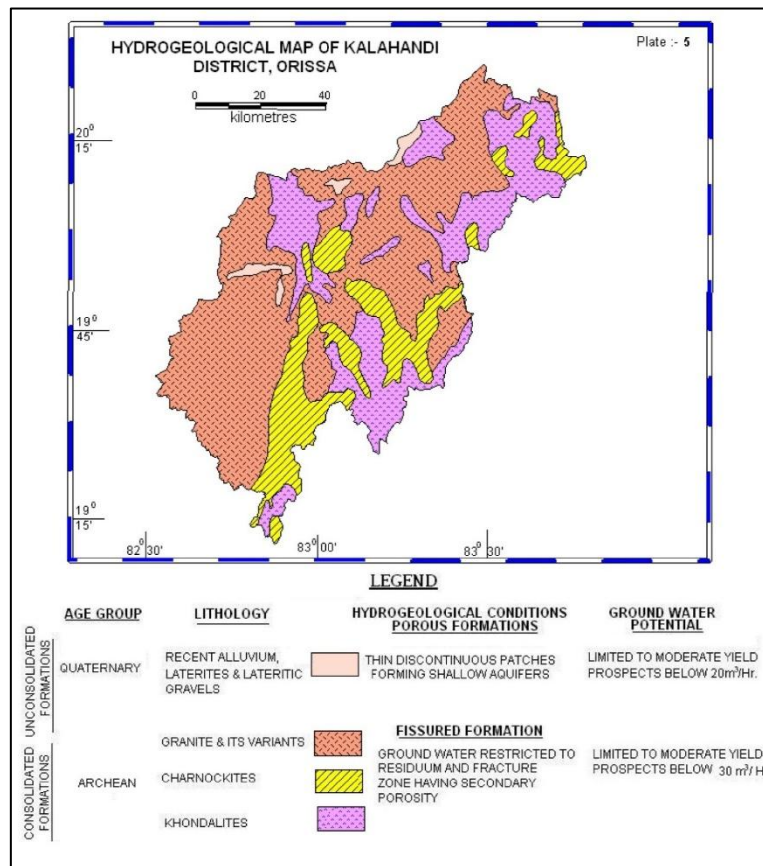


Figure 6: Hydrogeological map of Kalahandi district

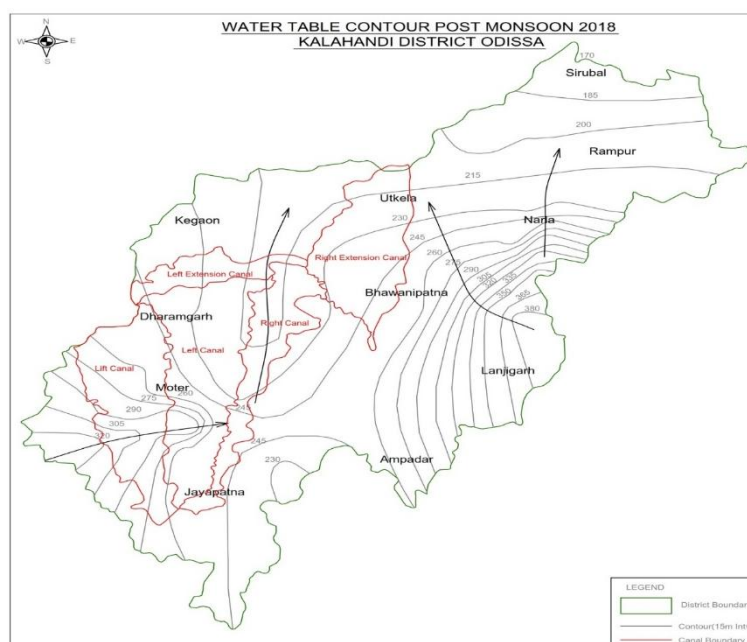


Figure 7: Post Monsoon Water Table contour of Kalahandi District, Odisha 2018

5. Ground Water Resources and Irrigation Potential

The ground water resources and irrigation potential of Pre-project period (1997- Level) is given in table-4 and of post-project period in table-5 below:

Table 4: Ground water Resources and Irrigation Potential (Pre-project period)

Sl. No.	Block	Replenishable GW Resources (Ham)	Utilizable Resources Irrigation (Ham)	Gross Annual Draft (Ham)	Balance GW Resources (Ham)	Stage of GW Development (%)
1.	Bhawanipatna	5242	4010	912	3817	14.32
2.	Dharamgarh	4112	3145	390	3222	7.80
3.	Golamunda	4864	3721	566	3738	9.59
4.	Jaipatna	4732	3613	247	4841	4.30
5.	Junagarh	5577	4267	803	4179	11.85
6.	Kalampur	1666	1275	231	1265	11.41
7.	Kesinga	5361	4101	749	4032	11.51
8.	Koksara	5120	3917	469	4024	7.54

Table 5: Ground water Resources of Command Area (2017)-Post-Project

Sl. No.	Block	Net GW Availability	Ground Water Draft for Irrigation	Net GW Availability for Future Irrigation	Stage of GW Development (%)
1.	Bhawanipatna	6749.14	2666.49	3331.22	49.46
2.	Dharmagarh	3810.53	725.87	2595.78	30.24
3.	Golamunda	7035.67	2309.28	4276.83	38.34
4.	Jaipatni	4626.78	748.26	3404.85	25.50
5.	Junagarh	7409.10	1662.74	4961.44	31.80
6.	Kalampur	2495.70	377.73	1915.04	22.47
7.	Kesinga	6251.51	2609.99	2891.44	52.78
8.	Koksara	5423.23	1525.87	3428.54	36.05

5.1. Ground water Use for Irrigation & Net Balance Ground water Availability for Future Irrigation in Command Area Blocks

This is as given in table-6 below:

Table 5: Ground water Use for Irrigation & Net Balance Ground water Availability for Future Irrigation in Command Area Blocks

KALAHANDI										
S. No.	Assessment Unit/ District	2004			2009			2013		
		Existing Gross Ground Water Draft for irrigation	Net Ground Water availability for future irrigation Development (10-11-14)	Stage of Ground Water Development $\{(13/10)*100\}\%$	Existing Gross Ground Water Draft for irrigation	Net Ground Water availability for future irrigation Development (10-11-14)	Stage of Ground Water Development $\{(13/10)*100\}\%$	Existing Gross Ground Water Draft for irrigation	Net Ground Water availability for future irrigation Development (10-11-14)	Stage of Ground Water Development $\{(13/10)*100\}\%$
1	Bhawanipatna	1265	4492	25.19	1358	3850	29.43	1618.15	3589.85	33.36
2	Dharmagarh	599	6350	12.11	647	3899	18.73	766.95	3779.05	20.91
3	Golmunda	823	3449	21.26	1020	4486	21.36	1234.96	4271.04	24.89
4	Kesinga	1142	3171	29.17	1231	3382	29.34	1508.97	3104.03	34.30

5	Jaipatna	457	7914	8.00	324	3675	13.93	452.95	3546.05	16.51
6	Junagarh	973	9420	12.03	882	7729	14.04	1109.04	7500.96	16.33
7	Kalampur	389	3290	13.00	444	2254	20.07	559.86	2138.14	23.39
8	Karlamunda	352	6818	8.29	359	4285	10.31	492.87	4151.13	12.79
9	Koksara	971	7039	14.14	838	7126	13.59	1096.91	6867.09	16.26
10	Lanjigarh	488	4107	13.38	588	4405	14.65	722.07	4270.93	17.13

5.2: Block-wise area Irrigated by Source (1996-97) for Kharif & Rabi Crops

For Pre-project period it is as outlined in table-7 and 8 respectively:

Table 6: Block-wise Area Irrigated by Source for Kharif Crops

Block	Major projects (Area)	Minor projects (Area)	Lift Irrigation Projects (Area) Govt+Pvt.	Ground water (Dug wells)	Other sources and W.H.S	Total Area (Ha)
Dharmagarh	7796	381	232	377	170	8956
Junagarh	7593	1863	629	763	276	11124
Jaipatna	9705	664	14	236	282	10901
Kalampur	1996	120	72	155	98	2441
Koksara	2791	3717	152	488	760	7908
Golamunda	-	1891	233	477	1888	4489
Total	29881	8636	1332	2496 (5%)	3474	45891

Table 7: Block-wise Area Irrigated by source for Rabi Crops

Block	Major projects (Area)	Minor projects (Area)	Lift Irrigation Projects (Area) Govt. + Pvt.	Ground water (Dug wells)	Other sources and W.H.S	Total Area (Ha)
Dharmagarh	-	50	232	188	1949	2419
Junagarh	-	220	629	366	2847	4062
Koksara	-	28	162	240	641	1071
Kalampur	-	-	72	50	1064	1186
Jaipatna	-	40	14	430	1067	1551
Golamunda	-	340	2323	240	1740	4643
Total	-	678	3432	1514 (10%)	9308	14932

5.3: Long-Term Ground Water Level (GWL) Trends

The position of long-term - gWL trends for pre and post project periods are as outlined in table 9(a), table 9(b) and table 9(c) below. The position of GWL depth verified in field (May 2019) for Left and Right Main canal system, block-wise is given in table-10.

Table 8(a): Long-term GWL trend (Pre-project period) – (1976-1998)

S. No.	Block	Location	Period	GWL-Trend	Rising /Falling
1.	Bhawanipatna	- Bhawanipatna - Karlapada - Pastikudi - Sargigoda - Dalguma	1976-98 1986-98 1986-98 1986-98 1988-98	1.09 0.80 1.01 -0.20 -0.44	Both Rising & falling
2.	Golemunda	- Kegaon - Dasapur	1987-98 1988-98	0.32 0.05	Rising & falling

S. No.	Block	Location	Period	GWL-Trend	Rising /Falling
		• Golamunda	1987-98	-0.21	
3.	Junagadh	• Baldiamal • Jaring • Moter	1989-98 1987-98 1978-98	-0.21 -0.06 0.83	Falling & Rising
4.	Kesinga	• Kesinga • Utkala • Tundla	1986-98 1986-98 1988-98	-1.09 -0.07 -1.39	Falling trends

Table 9(b): Long-term GWL trend (Post-project period) – (2000-2016)

Sl. No.	Block	Location	Period of Rise	
			From	To
1.	Bhawanipatna	Karlapada	2000 (6.6m)	2016 (4.0 m)
2.	Bhawanipatna	Pastikudi	2006 (6.55 m)	2016 (3.20 m)
3.	Golmunda	Daspur	2000 (5.92)	2011 (4.57)
4.	Golmunda	Kegaon	2000 (6.31)	2011 (4.91)
5.	Junagadh	Baldimal	2000 (5.26)	2018 (4.10)
6.	Junagadh	Jaring	2000 (6.12)	2011 (0.63)

Table 9(c): Position of GWL depth verified in field (May 2019)

Block	Location	GWL – May, 2019	Canal System
Junagarh	Koilgaon Disty (V. koilgaon)	3.50	RMC
Kalampur	Kalampur Minor (V- Kalampur)	2.00	RMC
Jaypatna	Nagphani Disty (V- Nagphani)	1.75	LMC
Jayaptna	Bijamara Disty (V- Bijamara)	2.20	LMC
Junagarh	Chhuriagarh Branch Canal (V- Banda Kutra)	2.50	LMC
Dhamagarh	V- Kashibahal (Canal Colony) Khairapadan Disty	2.30	LMC
Junagarh	Ambadola Disty (V- Ambadala)	2.20	LMC

5.4. Block-wise/Canal command –wise Irrigated & Rainfed Area (2015 level)

Percent irrigated and rain-fed areas for blocks/canal commands for pre-project period is outlined in table -10 below:

Table 9: Block-wise Irrigated & Rain-fed Area (2015)

S. No.	Block	IR (Ha)	%	RF (Ha)	%	Total
1	Dharmagarh (LEC)	27845	45.73	33047	54.27	60892
2	Golamunda (LEC)	11955	18.69	51999	81.3	63954
3	Jaipatna (LMC & RMC)	27925	57.06	21009	42.93	48934
4	Junagarh (LMC & RMC)	53207	71.89	20797	28.1	74004
5	Kalampur (LMC & RMC)	17704	71.28	7131	28.71	24835
6	Koksara (LMC)	9827	19.09	41627	80.9	51454
7	Bhawanipatna (REC)	8527	12.28	60889	87.71	69416
8	Kesinga (REC)	10408	22.2	36857	77.97	47265

6. Assessed Future Irrigation Coverage Areas in Commands:

Percent additional irrigation coverage area (Ha) for various canal command systems under study is given below in Tables 11 to 15

Table 10: Original UIIP Project: Right Bank Canal

Sl .	Block	Recharge worthy Area (ha)	Net GW Availability (ham)	Existing GW Draft (Irrigation) (ham)	Net GW Availability for Future Irrigation (ham)	Block Area in Command (ha)	Proportionate Net GW Availability (ham)	Proportionate Net GW Availability for future Irrigation (ham)	% Additional Irrigation Coverage Area (ha)		GW Status
									Area (ha)	% of block area	
1	Jaypatna	330207	4761	453	3456	3179	455.78	330.9	271.23	8.5	MS
2	Kalamapur	14097	3044	560	2138	6072	1311.14	920.9	754.83	12.43	S
3	Golamunda	62189	6208	1235	4271	288	28.75	19.8	16.23	5.6	NS
4	Junagadh	64698	9686	1109	7500	22698	3398.14	2631.2	21.72	9.50	S
	= 1.22m		Note: S = Significant		NS = Non significant		MS = Moderately significant				

Table 11: Original UIIP Project: Left Bank Canal

Sl .	Block	Recharge worthy Area (ha)	Net GW Availability (ham)	Existing GW Draft (Irrigation) (ham)	Net GW Availability for Future Irrigation (ham)	Block Area in Command (ha)	Proportionate Net GW Availability (ham)	Proportionate Net GW Availability for future Irrigation (ham)	% Additional Irrigation Coverage Area (ha)		GW Status
									Area (ha)	% of block area	
1	Dharmagarh	35191	5355	767	3779	5039	766.78	541.1	444.5	8.8	MS
2	Golmunda	62189	6208	2138	4271	3286	328.02	225.7	185.0	5.62	MS
3	Jaypatnam	33207	4761	453	3456	13869	1988.44	1443.4	1183.11	8.53	MS
4	Junagadh	64678	9686	1109	7500	24379	3650.93	2827.0	2317.21	9.50	MS
5	Kalamapur	14097	3044	560	2138	14059	3035.79	2132.2	1747.70	12.4	S
6	Kokasara	39064	8691	1096	6867	1106	246.06	194.4	159.34	14.4	S
	= 1.22		Note: S = Significant		NS = Non significant		MS = Moderately significant				

Table 12: Original UIIP Project: Right Extension Canal System

Sl .	Block	Recharge worthy Area (ha)	Net GW Availability (ham)	Existing GW Draft (Irrigation) (ham)	Net GW Availability for Future Irrigation (ham)	Block Area in Command (ha)	Proportionate Net GW Availability (ham)	Proportionate Net GW Availability for future Irrigation (ham)	% Additional Irrigation Coverage Area (ha)		GW Status
									Area (ha)	% of block area	
1	Bhawanipatnam	50953	6412	1618	3590	37784	4754.79	2662.2	2182.1	5.8%	NS
2	Kasinga	46874	5365	1509	3104	8703	996.10	576.3	472.4	5.4%	NS
			Note: S = Significant		NS = Non significant		MS = Moderately significant				

Table 13: Original UIIP Project: Left Extension Canal System

Sl .	Block	Recharge worthy Area (ha)	Net GW Availability (ham)	Existing GW Draft (Irrigation) (ham)	Net GW Availability for Future Irrigation (ham)	Block Area in Command (ha)	Proportionate Net GW Availability (ham)	Proportionate Net GW Availability for future Irrigation (ham)	% Additional Irrigation Coverage Area (ha)		GW Status that Emerges (S/NS)
									Area (ha)	%	
1	Dharmagadh	35191	5355	767	3779	2719	413.74	292.3	239.3	8.8	MS
2	Junagadh	64698	9686	1109	7500	263	39.37	30.5	25.0	9.5	S
3	Golamunda	62189	6208	1235	4271	11315	1129.51	777.1	637.0	5.6	NS
			Note: S = Significant		NS = Non significant		MS = Moderately significant				

Table 14: Lift Irrigation Project Command

S.No .	Block	Recharge worthy Area (ha)	Net GW Availability (ham)	Existing GW Draft (Irrigation) (ham)	Net GW Availability for Future Irrigation (ham)	Block Area in Command (ha)	Proportionate Net GW Availability (ham)	% Additional Coverage Area (ha)	GW Status that Emerges (S/NS)
1	Dharamagadh	35191	5355	766.95	3779.05	10155.5	1545.36	10.74	S
2	Jaypatnam	33207	4761	452.95	3546.05	20119.4	2896.05	10.68	S
3	Koksora	39064	8691	1096.91	6867.09	23222.9	5166.66	17.55	S
			Note: S = Significant		NS = Non significant				

7. Quantum of Ground water for Conjunctive Use in UIIP Command

The percentage of additional area of project blocks that can be irrigated with conjunctive use of ground water as worked out is outlined below:

- (a) For Right Bank Canal of UIIP: Net Groundwater availability for future use applicable to block ranges from 19.8 Ham to 2631.2 Ham with Golamunda block having minimum GW Availability and Junagadh having the maximum. Accordingly, the percentage of additional area of the blocks that can be irrigated with conjunctive use of ground water has been worked out & the same is given below;

- Jaypatnam - 8.5 % (MS)
- Kalampur - 12.43 % (S)
- Gloamunda - 5.6 % (NS)
- Junagadh - 9.5 % (S)

If the area of the block in excess of 10% is covered with conjunctive use of ground water, the same is reckoned as “Significant(S)”, whereas the area between 5 & 10% is reckoned as “Moderately Significant” (MS) and area < 5% as “Non-Significant(NS)”.

It may be noted that two blocks namely Kalampur and Junagadh fall under “Significant(S)” category for conjunctive ground water use and only one block namely Golamunda falls under “Non-Significant(NS)” category for conjunctive ground water use. The Jaypatnam falls under “Moderately Significant (MS)” Category.

- (b) For Left Bank Canal of UIIP: The “Net GW Availability for future irrigation” proportionate to the block area in command of the above block ranges from 194.4 Ham to 2827 Ham with Kokasara block having minimum GW Availability and Junagadh having the maximum. Accordingly the percentage of additional area of the blocks that can be irrigated with conjunctive use of ground water has been worked out & the same is given below;

- Dharmagadh - 8.8 % (MS)
- Jaypatnam - 8.53 % (MS)
- Kalampur - 12.43 % (S)
- Gloamunda - 5.62 % (NS)
- Junagadh - 9.5 % (MS)
- Kokasara - 10.4% (S)

It is to be noted that three blocks namely Dharamgadh, Jaypatnam , and Junagadh falls under “Moderately Significant (MS)” category for conjunctive ground water use and only one block namely Golamunda falls under ”Non-Significant(NS)” category for conjunctive ground water use. Also two blocks namely Kalampur and Kokasara fall under “Significant (S)” category.

8. Assessment of Pond percolation as recharge to Groundwater in Command Area

The location Map of Ponds in Indravati irrigation Command is as recharge to ground water given in fig 4 and estimated percolation for four Canal segments under study is given in table 16 below:

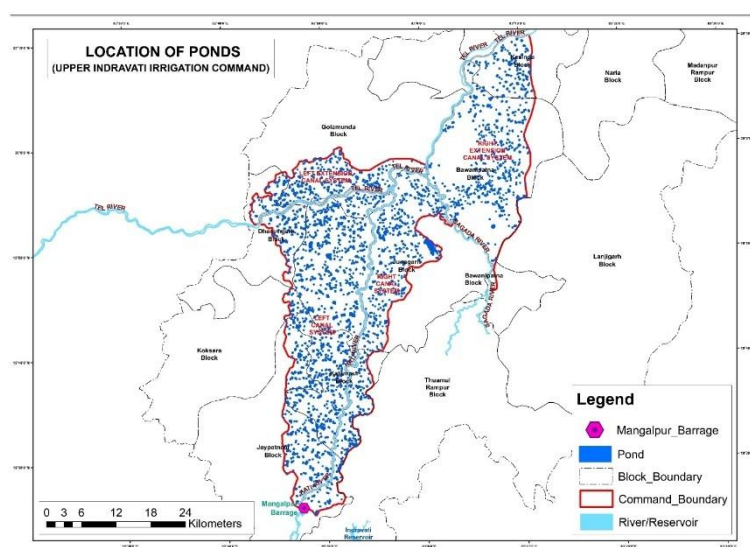


Figure 8: Location of Ponds (Upper Indravati Irrigation Command)

Table 15: Estimated Pond percolations recharge to ground water in command area

S. No.	Command	Block Name	No. of Ponds	Area in ha	Volume of impounded water in ham considering Av. depth water column - 0.8m	Ground water Recharge from ponds in ham (Considering 60%)	Quantity in MCM
1	Right Canal System (559)	Junagarh	383	495.7	396.56	237.936	2.38
		Kalampur	128	113.41	90.728	54.4368	0.54
		Jaypatna	47	38.66	30.928	18.5568	0.18
2	Right Extension (661)	Kesinga	136	143.3	114.64	68.784	0.69
		Bhawani Patna	525	353.85	283.08	169.848	1.69
3	Left Extension (312)	Golamunda	257	240.16	192.128	115.2768	1.15
		Dharmgarh	55	54.15	43.32	25.992	0.26
4	Left Canal Extension (1182)	Golamunda	59	41.14	32.912	19.7472	0.19
		Junagarh	472	547.32	437.856	262.7136	2.63
		Dharmgarh	75	123.73	98.984	59.3904	0.59
		Koksara	26	21.33	17.064	10.2384	0.10

		Kalampur	304	324.2	259.36	155.616	1.56
		Jaypatna	246	274.67	219.736	131.8416	1.32
Total			2713	2771.6	2078.715	1330.38	13.30 MCM

9. Estimated recharge to Ground water from applied Irrigation water to Paddy Fields in Command

For Left Bank Canal and Right bank canal, it is illustrated in table 17 & 18 below.

Table 16: Estimated recharge to Ground water from Applied Irrigation water to Paddy Fields in Command: For Left Bank Canal

Left Bank Canal (LBC)		Kharif				Rabi			
S. No.	Year	Water Applied (Ham)	Area (Ha)	Seepages from Canal	Percolation from Paddy Field (return flow)	Water Applied (Ham)	Area (Ha)	Seepages from Canal	Percolation from Paddy Field (return flow)
1	2000-2001	10888	22454	1633.2	3266.4	21136	8391	3170.4	6340.8
2	2001-2002	17178	22454	2576.7	5153.4	26966	7560	4044.9	8089.8
3	2002-2003	18548	22457	2782.2	5564.4	9693	16582	1453.95	2907.9
4	2003-2004	9262	22457	1389.3	2778.6	28532	17553	4279.8	8559.6
5	2004-2005	30085	22454	4512.75	9025.5	41356	30418	6203.4	12406.8
6	2005-2006	24861	38844	3729.15	7458.3	48749	30899	7312.35	14624.7
7	2006-2007	40187	38844	6028.05	12056.1	56410	30193	8461.5	16923
8	2007-2008	33013	38755	4951.95	9903.9	26863	37489	4029.45	8058.9
9	2008-2009	29073	50783	4360.95	8721.9	49230	33046	7384.5	14769
10	2009-2010	28443	50783	4266.45	8532.9	39103	37122	5865.45	11730.9
11	2010-2011	35642	50783	5346.3	10692.6	46493	10586	6973.95	13947.9
12	2011-2012	30752	50783	4612.8	9225.6	14913	37506	2236.95	4473.9
13	2012-2013	37855	50783	5678.25	11356.5	42894	37506	6434.1	12868.2
14	2013-2014	33830	50783	5074.5	10149	44064	37506	6609.6	13219.2
15	2014-2015	43872	50783	6580.8	13161.6	49693	37506	7453.95	14907.9
16	2015-2016	48506	50783	7275.9	14551.8	20837	25509	3125.55	6251.1
17	2016-2017	24123	50783	3618.45	7236.9	50574	31678	7586.1	15172.2
18	2017-2018	24093	50783	3613.95	7227.9	40368	32552	6055.2	12110.4
Total (in HAM)		520211	736549	78031.65	156063.3	657874	499602	98681.1	197362.2
Total (in MCM)		5202.11	7365.49	780.3165	1560.633	6578.74	4996.02	986.811	1973.622

Table 17: Estimated recharge to Ground water from Applied Irrigation water to Paddy Fields in Command: For Right Bank Canal

Right Bank Canal(RBC)		Kharif				Rabi			
S.No.	Year	Water Applied (Ham)	Area (Ha)	Seepages from Canal	Percolation from Paddy Field(return flow)	Water Applied (Ham)	Area(Ha)	Seepages from Canal	Percolation from Paddy Field(return flow)
1	2000-2001	5863	15925	879.45	1758.9	Drought Year			
2	2001-2002	9250	16327	1387.5	2775	14520	11305	2178	4356
3	2002-2003	9988	16327	1498.2	2996.4	5220	3120	783	1566
4	2003-2004	4987	16327	748.05	1496.1	15363	11543	2304.45	4608.9
5	2004-2005	16200	16336	2430	4860	22269	12243	3340.35	6680.7
6	2005-2006	13387	16336	2008.05	4016.1	26250	12814	3937.5	7875
7	2006-2007	21639	16727	3245.85	6491.7	30375	12848	4556.25	9112.5
8	2007-2008	17776	22306	2666.4	5332.8	14465	13073	2169.75	4339.5
9	2008-2009	15654	22306	2348.1	4696.2	26508	17844	3976.2	7952.4
10	2009-2010	15316	23703	2297.4	4594.8	21055	17844	3158.25	6316.5
11	2010-2011	19192	23703	2878.8	5757.6	25034	9244	3755.1	7510.2
12	2011-2012	16559	23708	2483.85	4967.7	8030	3079	1204.5	2409
13	2012-2013	20383	24123	3057.45	6114.9	23097	18648	3464.55	6929.1
14	2013-2014	18216	24123	2732.4	5464.8	23727	18648	3559.05	7118.1
15	2014-2015	23624	24123	3543.6	7087.2	26758	22393	4013.7	8027.4
16	2015-2016	26119	24750	3917.85	7835.7	11220	3400	1683	3366
17	2016-2017	11128	25116	1669.2	3338.4	9045	23012	1356.75	2713.5
18	2017-2018	10743	25846	1611.45	3222.9	0	0	0	0
Total (in HAM)		276024	378112	41403.6	82807.2	302936	211058	45440.4	90880.8
Total (in MCM)		2760.24	3781.12	414.036	828.072	3029.36	2110.58	454.404	908.808

10. Summary Analysis-UIIP Project, Odisha

Micro-zonation of GWL status,ground water availability, changes in status of ground water development over 20-years in Command area blocks, blockwise area irrigated and rainfed areas and scope for future ground water-based irrigation in project command are described as below:-

10.1: Micro-zonation of Command based on Groundwater table Depth (May 2018) is as shown in figure 5:

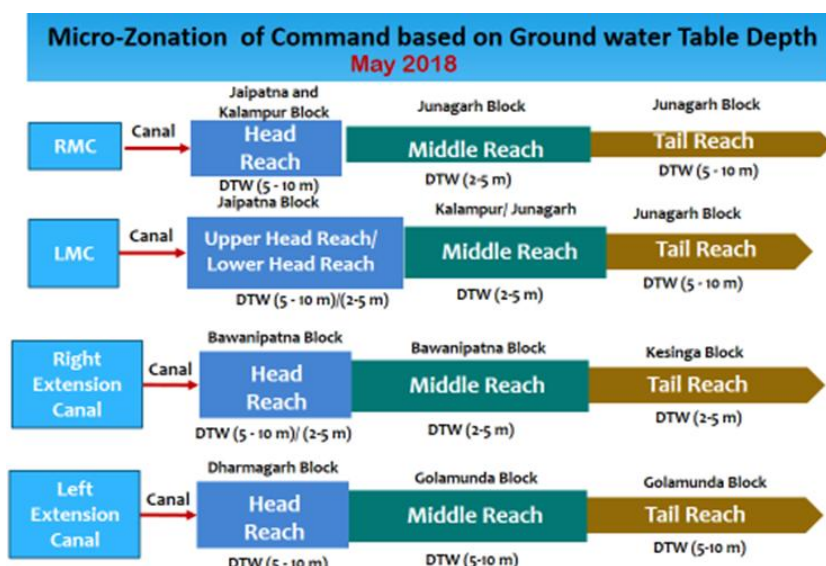


Figure 9: Micro-zonation of Command based on Groundwater table Depth (May 2018)

10.2: Over-all GWL Status in Command (1995-2018): it is as outlined below in table 19

Table 18: Over-all GWL Status in Command (1995-2018)

LMC	1995-2000	Mostly steady levels (Pre-project)
	2000-2018	Steady Rise and Fall in Levels (Post-project)
RMC	1995-2000	Mostly steady levels (Pre-project)
	2000-2018	Mostly Steady Rise in Levels (Post-project)
Right Ext. Canal	1995-2000	Both rising and falling levels (Pre-project)
	2000-2018	Stable and rising levels (Post-project)
Left Ext. Canal	1995-2000	Consistent levels: 5-7 m (bgl) (Pre-project)
	2000-2018	Consistent levels: 5-6 m (bgl) (Post-project)

10.3: Status of Ground water Availability in various Canal command segments (as on 2017)

It is as illustrated in Figure 6 below:

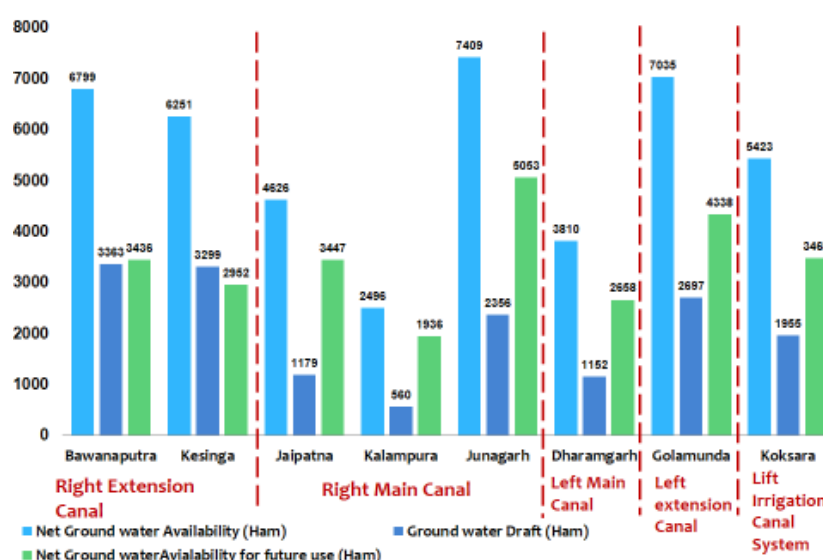


Figure 10: Status of Ground water Availability in various Canal command segments (as on 2017)

10.4: Changes in status of Ground water development over 20-years in Command and area blocks (1997-2017)

The status is outlined in table 20.

Table 19: Changes in status of Ground water development over 20-years in Command and area blocks (1997-2017)

S. No.	Canal system	1997 Stage of Ground Water development (%)	2017 (Stage of Ground Water development (%))
1	Right main canal	4-12%	22-38%
2	Left Main canal	5-12%	20-38%
3	Right Ext. Canal	11-14%	50-52%
4	Left Ex. Canal	8-12%	30-38%

10.5: Irrigation Status in Commands

(A) Irrigation Potential (IP) created with Surface Irrigation:(more than 90%)

- (a) In Kharif: 170,180 Ha
- (b) In Rabi: 107,756 Ha
- (c) Total :2,78,000 Ha

(B) Irrigation Potential (IP) created with ground water: 21,189 Ha(only 7%)

10.6: Scope for Future Ground water-based irrigation in Project Command

Canal command wise scope for future ground water based irrigation in project commands are as follows:

(1) RMC Area:

Junagarh and Kalampur parts of blocks have significant balance ground water potential to cover additional irrigation areas of 2156 ha and 754 ha respectively in the command.

(2) LMC Area:

Only Kalampur part of the block falling in this segment of command have potential to irrigate additional area of 1747 ha under future irrigation.

(3) Right Extension Canal Area:

Ground water availability in blocks of this segment of command is meagre and non-significant to meet any future requirement of irrigation.

(4) Left Extension Canal Area:

The blocks in this part of canal segment also bear insignificant balance ground water quantities to meet any future needs of irrigation.

(5) Lift Irrigation Area: It has significantly large balance ground water availability for future need of irrigation in the area.

11. Summary & Conclusion

- i. The UIIP Command in Kalahandi district of Odisha is a drought prone area. Dry spells (Mild Drought) occur every 2.5 Years and Normal Drought every 6 years.
- ii. Project command is underlain by shallow weathered (0-15m) and deep fractured (12-180m) hard rock aquifer system having moderate yield potential by wells & borewells.
- iii. Irrigation canal Network systems are left Main canal system (LMC), Right Main Canal (RMC) System, Left & Right Extension Canal System and Lift Irrigation System.
- iv. Annual replenishable Ground Water in blocks covering the Irrigation Commands is of sizeable magnitude. Pre-project stage of ground water development was in the range of 4.30 to 14.32%. The post-project stage of ground water development and use (2017) is in the range of 22.47 to 52.78%. There is ample scope for stepping up ground water development as & when needed.
- v. The development of ground water exhibits wide inter-command as well as intra-command variations. The ground water development ranges from 22-31% in command (RMC) to 49-52% in

- command (Right Extension Canal) with overall average development being 34% in the Kalahandi district. Ground Water development in the area has increased from an average of 10% in 1977 to average 34% in 2017. The increasing trend in GWD is found in all Command segments.
- vi. Pre-project Ground Water Levels (1998-98) were mostly stable between 5 and 10 m (below land surface). Post-project levels (2018) were variously between 2-5 & between 5-10 m (bgl) in the different command segments. Ground water in the area flows mostly northwards & locally eastwards in the UIIP command.
 - vii. Long-term GWLs (1976-88) registered both rising & falling trends. Post-project period (2002-2018) registered rising trends with rise variously ranging from 1.30 m to 3.5m. May, 2019 levels of ground water were found to be between 2 & 4m (bgl) in different command segments under study.
 - viii. Long-term GWL Trend in the area shows rise, the average being 0.22 m/yr.
 - ix. Quantum of Ground Water for Conjunctive use in UIIP Command is assessed:
 - In RMC of UIIP, out of 4 blocks, the significant percentage of additional area (about 10% or more) that can be irrigated with conjunctive use of ground water has been found to occur only in blocks of Junagarh (9.5%) and Kalampur block (12.43%).
 - For LMC of UIIP, 2 out of six blocks namely Koksara (10.4%) and Kalampur (12.43%) fall under significant category for conjunctive ground water use.
 - x. The water balance is strongly affected by agricultural practices and ground water recharge mainly originating from irrigation losses.

REFERENCES

- Walker, G. R., Horne, A. C., Wang, Q. J., & Rendell, R. (2021). Assessing the impact of irrigation efficiency projects on return flows in the South-Eastern Murray–Darling Basin, Australia. *Water*, 13(10), 1366. <https://doi.org/10.3390/w13101366>
- Central Water Commission (2012), *Water use Efficiency Studies of Upper Morhar Irrigation Project Bihar*.
- Hebig, K. H., Ito, N., Scheytt, T., & Marui, A. (2012). Review: Deep groundwater research with focus on Germany. *Hydrogeology Journal*, 20(2), 227–243. <https://doi.org/10.1007/s10040-011-0815-1>
- Ground water Resource Availability, Utilization and Stage of Development, Madhya Pradesh.*
- Chaube, U.C., Pandey, A., Singh, V.P. (2023). Use of Ground Water in Canal Command Area. In: Canal Irrigation Systems in India. Water Science and Technology Library, vol 126. Springer, Cham. https://doi.org/10.1007/978-3-031-42812-8_12
- A STUDY ON IMPROVING SAND TRAP IN a LARGE SCALE OF IRRIGATION SCHEME. (2016). In *2nd World Irrigation Forum (WIF2)* (p. W.1.3.03). https://www.icid.org/wif2_full_papers/wif2_w.1.3.03.pdf
- Ch. Praveenkumar, V. Jothiprakash; Spatio-temporal trend and homogeneity analysis of gridded and gauge precipitation in Indravati River basin, India. *Journal of Water and Climate Change* 1 March 2020; 11 (1): 178–199. doi: <https://doi.org/10.2166/wcc.2018.183>



Assess & Evaluate Impact of Bore-Charger Activity on nearby Water Bodies: A Case Study of Khalad, Purandar, Maharashtra India

Vinit Phadnis

Research Scholar, Department of Geology, Savitribai Phule Pune University, Pune, India.
Currently: m/S Urdhvam Environmental Technologies Pvt Limited.
E-mail: vinit@urdhvam.com

Abstract

Groundwater is absolutely vital for sustaining over 80% of agricultural irrigation in India, underscoring its critical importance in food production. To effectively address the pressing challenge of groundwater sustainability, innovative methods such as Bore-charger offer powerful solutions. The study area is situated on the Deccan basalts, formed millions of years ago by volcanic eruptions, and it is characterized by complex geological formations with varying basaltic layer thicknesses, classified as 'simple' and 'compound' types. Hydrogeological studies in this region rely on a comprehensive range of data sources, including rainfall patterns, geological structures, and hydrographic data, to manage groundwater resources with precision. Given the intricate nature of the basalt aquifer system, the application of innovative approaches like Bore-charger is not just important—it's essential. Bore-charger conducts thorough hydrogeological investigations and effectively perforates borewell casings to recharge deep aquifers with freshwater from unconfined aquifers. This process significantly enhances both the quantity and quality of groundwater and revitalizes failing or low-yielding borewells, paving the way for sustainable water management. The study emphatically demonstrates the positive impact of Bore-charger on nearby water bodies and wells, showing no adverse effects on groundwater levels. Bore-charger-equipped borewells consistently maintain water levels until late March, ensuring a reliable supply of water crucial for agricultural and drinking water security. Additionally, there is a marked improvement in water quality, reinforcing the positive outcomes for groundwater sustainability and enhancement. In summary, Bore-charger stands out as a powerful solution to the challenges of groundwater sustainability and quality improvement, with implications that extend well beyond the study area.

Keywords: Artificial Recharge, Bore-charger, impact, water level

Introduction

Water is fundamental to life on Earth and is often considered more valuable than commodities such as oil and milk, particularly in certain regions. Covering approximately 71% of the planet's surface, water plays a crucial role in Earth's ecosystem. The hydrological cycle comprises about 97.5% saltwater in oceans, with freshwater constituting just 2.5%, spread across ice caps, glaciers, groundwater, lakes, rivers, soil, and the atmosphere.

Throughout history, water has been vital for the growth of civilizations alongside major rivers like the Indus, Ganges, Nile, Tigris, and Huang He. However, increasing populations and poor resource management practices have led to significant overexploitation of water reserves, creating a critical issue of water scarcity.

The uneven distribution of water, exacerbated by rapid population growth and human activities, poses considerable challenges. It is projected that many people worldwide will experience water scarcity in the coming decades, potentially impacting living standards.

Oceans serve as major reservoirs, maintaining the water cycle through evaporation, condensation, and precipitation, which support terrestrial water sources. Disruption of this cycle threatens the balance needed for life.

Moreover, water is essential for food security, industrial production, and environmental preservation. The escalating demand for water, combined with insufficient management, intensifies scarcity issues, necessitating immediate action to ensure sustainable usage for future generations (Narayan Hegde et al., BAIF Indian Science Congress, 2012).

While approximately 70% of the Earth's surface is water, 97.5% is saltwater, leaving only about 35 million cubic kilometers of freshwater. Of this, 68.7% is frozen in ice caps, 30% contained in lakes, and only 2% is found in rivers. Due to extraction limitations, only about 1% of total freshwater is usable for human needs [(Annon, 2006), Ref. -Anonymous 2006 Water - A Shared Responsibility, United Nations World Water Department Report].

Historically seen as abundant, water is unevenly distributed across continents, with some countries experiencing surplus while others face severe scarcity. Asia holds 36% of global freshwater reserves, while Africa has access to 11% for 13% of its population. Patterns of water use differ widely based on cultural practices, lifestyle, and levels of industrialization.

Overall, water is chiefly used for agricultural, domestic, and industrial purposes, and is key to hydropower, fisheries, transportation, and biodiversity. The allocation of water resources varies by country, reflecting each nation's lifestyle and development.

Table 1, highlights that developing countries use comparatively less water for agriculture than for industrial and domestic purposes. Some developing countries, such as India and those in Africa, allocate 80 to 90% of their water resources for agricultural purposes, and only 5 to 12% is used for industrial activities highlighting insufficient utilization of water for agriculture and a lack of investment in industrial development amid urbanization. As per data presented in Table 2, per capita water usage in India will increase from 99 litres per day to 167 litres per day by 2050. In contrast, water consumption in the United States is expected to decrease from 587 litres per day to 484 litres per day.

Study Area

The present study is focused on the area surrounding Khalad Village in Purandhar Taluka, Pune District (Figure 1). Khalad is a Gram Panchayat located to the East of Saswad town and is home to a population of 3,104 residents, primarily consisting of marginal farmers. The village comprises a total of 635 families. According to the 2011 Population Census, Khalad has 1,559 males and 1,545 females.

Topographically the area has a gentle slope toward the east, with elevations ranging from approximately 730 to 835 meters, resulting in an elevation difference of over 105 meters. Overall, the central part of the watershed is relatively flat. This region experiences a sub-tropical to tropical temperate monsoon climate, characterized by hot summers and general dryness throughout the year, except during the southwest monsoon season. There are three distinct seasons: summer, monsoon, and winter. The summer months span from February to May, with maximum temperatures ranging between 30°C and 40°C, peaking in May. The monsoon season lasts from June to the end of September and brings moderate rainfall, while winter occurs from October to January. The area falls under moderate to low rainfall conditions, with meteorological data indicating an average annual rainfall of 518 mm. Most of the total precipitation occurs between June and September, with an average of only about 40 rainy days per year. (Table 3 and Fig 2 for more details).

Geology of the area

The project area is entirely underlain by Deccan basalts, also known as Deccan Traps or Deccan Trap Basalts. These formations were created from lava eruptions approximately 65 million years ago (Fig. 3). The lava flows vary in thickness, ranging from a few meters to tens or even hundreds of meters. Each lava flow can be divided into units and subunits.

Generally, Deccan basalts can be categorized into two groups: 'simple' and 'compound', based on the viscosity of the primary lava (Deshmukh, 1988; Kale and Kulkarni, 1992).

Simple basalt flows are characteristic of classic flood basalts, formed by the effusive eruption of large quantities of low-viscosity lava from open fissures. In contrast, compound flows result from either

explosive activity involving more viscous lavas or from areas at the distal ends of simple flows, where increased viscosity occurs due to cooling and de-gassing.

Both types of basalt flows tend to weather differently, even across small outcrops. In the project area, basalt lavas are predominantly classified as "compound" lava flows, which belong to the Ambenali Formation of the Wai Subgroup (Subbarao, 1986) or the Purandhargad Formation of the Diveghat Subgroup within the Sahyadri Group (Godbole et al., 1996).

Compound flow basalts lose a significant amount of their volatile gases before extrusion, resulting in more viscous lava. This increased viscosity causes the remaining volatile gases to become trapped within the rapidly solidifying lava. The lava displays rubbly surfaces on both the upper and lower sections. The fragmentation of the upper surface occurs due to the disruption of the viscous crust caused by the movement of the lava flow beneath it. Some compound flows might lack a compact middle layer. Although there is a clear distinction between the two types of lava flows, it is common to see gradations between simple and compound flows. The loss of volatiles and the cooling process can increase the viscosity of the lava, leading to changes in its physical characteristics (Macdonald et al., 1995).

Mapping basalt lavas can be labor-intensive. In the project area, the basalt units have been categorized into 'simple' types, including vesicular-amygdaloidal basalt units and compact basalt units. These units are further covered by black cotton soils and sandy loamy soils, approximately 2 to 5 meters thick.

In Plate 1, weathered Compact Basalt (CB) is visible along the roadside. Vesicular

Figure 4 presents the inferred geological map of the area. Compound flow is categorized into Compact Basalt (CB) and Vesicular Amygdaloidal Basalt (VAB). In this area, 22 distinct units have been identified (11 units of Compact Basalt and 11 VAB units of Vesicular Amygdaloidal Basalt).

Hydrogeology of the area

Hydrogeologically the area is primarily composed of Deccan Traps, featuring intertrappean beds from the Upper Cretaceous to Lower Eocene age. The exposed lava pile ranges from 620 to 1080 meters above mean sea level (AMSL) constituting 22 basalt units, categorized as Compact Basalt and Vesicular Basalt, constituting a significant portion of the region.

The yield of wells depends on the permeability and transmissivity of the encountered aquifer and can vary based on location, diameter, and depth. The basaltic lava flows are generally massive and fine-grained, exhibiting negligible primary porosity and transmissivity. Their yields, however, are enhanced due to the presence of secondary porosity that develops from fractures and jointing. Additionally, weathered zones ranging from 5 to 12 meters in thickness have formed in plains and depressions. Weathered, jointed, and fractured sections of the vesicular and massive basalt units are primary water-bearing horizons (Fig 5). It is important to note that these zones are neither continuous nor uniformly developed laterally or vertically, thereby, significantly impacting the success or failure of wells in the area.

The area witnesses three types of groundwater structures present: dug wells, bore wells, and dug-cum-bore wells (DCB), as well as dug wells with near-horizontal bores within the fractured basalt. The yield characteristics of these structures are.

Groundwater occurs in an unconfined state in the shallow aquifers tapped by dug wells at depths ranging from 8 to 28 meters. Water levels vary from 2.0 to 17.5 meters below ground level (bgl), and the yield of dug wells in basalt ranges from 20 to 90 cubic meters per day (m³/day). However, dug wells situated in more favourable locations can yield between 100 and 250 m³/day. Groundwater is predominantly utilized for irrigation, serving as the primary source for this region, which mainly supports the cultivation of sugarcane, pomegranates, and other cash crops.

The state government has drilled numerous bore wells fitted with hand pumps and electric motors to provide rural drinking water. The yields of these bore wells range from 500 to 3000 liters per hour (lph). In this taluka, groundwater development is mainly achieved through dug wells.

Groundwater exists under phreatic/unconfined to semi-confined conditions in the basalts. The shallow Aquifer-I, tapped by dug wells at depths of 5.6 to 28 meters, shows water levels ranging from 2.0 to 17.5 meters bgl during the pre-monsoon and from 0.2 to 12.0 meters during the post-monsoon. The yield in Aquifer-I varies from 5 to 100 m³/day. A deeper Aquifer-II is also present and accessed through bore wells, with depths ranging from 20 to 174 meters bgl. Water levels in this aquifer range from 2.3 to 60.0 meters bgl during the pre-monsoon and from 2 to 41.0 meters during the post-monsoon.

Groundwater System

The basalt aquifer system is complex and can only be described in general terms due to the numerous individual flows involved. Due to the intricate nature of this system and insufficient data available to map the flow patterns of each aquifer zone, individual basalt flows have been conceptually grouped. The depth to the water-bearing zones within the basalt varies significantly, reflecting the complicated groundwater dynamics in the aquifer.

In this area, the unconfined aquifer is composed of Compact Basalt and the Vesicular Amygdaloidal Basalt Unit

(Fig 6). The average thickness of this unconfined aquifer is approximately 10 meters.

The Deccan lavas present a noteworthy example of a groundwater system. The vesicular-amygdaloidal basalts and the compact basalts are lithologically distinct; however, their physical proximity often creates a single hydrogeological unit or groundwater system (Kulkarni H., 2000).

Variations in hydraulic gradient across the region are partly due to secondary recharge and discharge, as well as spatial differences in the hydraulic characteristics of the basalt aquifer system. The range of hydraulic conductivities reflects the heterogeneous nature of the basalts. High values are often related to local geological structures and the thickening of interflow zones, low values may result from offsetting interflow zones or reduced pore spaces due to the deposition of secondary minerals. This variability means that certain regions of the basalt can effectively transmit water, while others have limited capacity. Figure 7 represents a conceptual cross-section of the Khalad Watershed.

Movement of water through basaltic formations is influenced by several factors, including the topography over which the flows occurred, the deposition of interbeds, and tectonic activity creating a significant variation in the lateral continuity, thickness, and composition of lava flows. Typically, only 5 to 10 percent of the thickness of an individual basalt flow consists of the interflow zone. The interflow zone between lava flows is highly heterogeneous and allows significant water transmission.

The interflow zones are bordered by less permeable, more massive portions of rock that are less effective at moving water through the aquifer. While lateral water flow primarily occurs through fractures and joint systems, it is likely negligible compared to the flow through interflow zones, which happens through primary features such as flow vesicles. Although vertical movement of groundwater in interflow zones is considerably less than lateral movement per unit area, the overall vertical movement can be large. Additionally, this vertical movement of groundwater is highly variable due to the heterogeneity of the interflow zones.

Overall, the findings regarding the aquifers in the investigated area suggest that the net direction of groundwater flow between overlying aquifers is generally upward. There is direct recharge from precipitation infiltrating the primary recharge zones. The deeper aquifers are far and at a higher elevation than the shallower aquifers. This difference creates a general upward driving force for groundwater.

A deeper groundwater system represents the relatively untapped source of non-monsoon water supply, primarily accessed through bore wells in the area. Most dug wells have effectively penetrated the groundwater system, revealing a water table surface.

Based on the surface and subsurface observations, a three-dimensional conceptual model for the Khalad watershed has been developed (Fig. 8) to enhance visualization.

Methodology

Recharge of a borewell occur only during rainfall. The recharge rates of borewells do not match the stormwater generated, leading to significant amounts of stormwater wasting and flowing away.

In the case of the Patented Bore-charger Technique, trained experts utilize a borewell scanning camera system to conduct a comprehensive hydrogeological investigation and lithological mapping. They analyze primary field observations alongside secondary data, including geological maps and groundwater hydrogeology, to gain insights into groundwater aquifer systems.

Based on this thorough investigation, the Bore-charger tool creates precise perforations in the impermeable borewell casing from the inside at the appropriate depth. This process allows water from the upper aquifer to enter the borewell, injecting freshwater into the deeper aquifer layers during and after the monsoon season. As a result, this technique significantly enhances both the quantity and quality of groundwater, providing a sustainable water supply. This cost-effective technology can swiftly revive failed or low-yielding borewells.

This innovative approach involves puncturing the casing of an existing borewell in situ, without digging or excavation. This method significantly reduces the cost and time required for improving the yield. Traditionally, such interventions could only reach depths of up to 10 feet. However, this deeper puncturing technique ensures that only naturally filtered water enters the borewell. Additionally, it allows the unconfined aquifer to contribute water to the borewell during non-rainy seasons, providing more time for the confined aquifer to recharge. This process not only enhances the yield of the borewell but also recharges the confined aquifers, thereby increasing the duration of water availability. Figure 9 illustrates the conditions inside the borewell before and after the Bore-charger procedure.

The methodology for the Bore-charger Implementation Study consists of several essential steps. First, site selection criteria are established, considering factors such as accessibility and measurement ease to facilitate efficient data collection. Next, Borewells, Dugwells, and Water Bodies are identified, with one Borewell selected for the Bore-charger implementation. Nearby Dugwells and Water Bodies are included for monitoring purposes. Two Observation Borewells are chosen to track changes in groundwater levels after implementation. Baseline observations are then conducted at all selected sites, recording spatial attributes and initial water levels to establish the pre-implementation conditions. Following this, the Bore-charger technology is implemented in selected Borewell by established protocols, careful installation, and supervision by trained personnel. After implementation, water level observations are conducted to monitor changes in water levels and assess the impact of Bore-charger implementation on groundwater recharge. The collected data, including pre-and post-implementation water levels, is analyzed to evaluate the effectiveness of Bore-charger in enhancing groundwater recharge and improving water availability.

Instruments used for the study

Water Level sounder, measuring staff for water level measurements in borewells /dugwells and pH, Conductivity & TDS meters along with field test kit for measurement of Hardness.

Results and Observations

The primary goal of the Bore-charger technique is twofold. First, it aims to enhance the direct recharge of deeper aquifers using the water stored in the upper unconfined zones. This process not only boosts the overall yield of groundwater but also improves its quality.

Site 1 – Borewell Near Surface Water Reservoir & Borewell

Name of the Client: Ganesh Raskar

Figure 10(a) shows the site locations and Table 4 details the bore wells and reservoir. Table 5 documents the details of Observation Well Site 1.

Site 2 – Borewell Near Open Well & Borewell

Name of the Client: Mohan Raskar

The site location is shown in Figure 10(b), while Table 5 delivers details about the bore wells. Table 6 outlines the specifics of the site.

Site 3 – Borewell Near Open Well

Name of the Client: Gram Gaurav Pratishthan

The location of the site is depicted in Figure 10(c), and Table 8 gives information regarding the bore wells and the reservoir. Table 5 presents the details for Well Site 3.

Site 4 – Borewell Near Surface Water Reservoir

Name of the client: Suresh Raskar

The site's location is shown in Figure 10(d), while Table 10 provides details and Table 11 outlines the information for Observation Well Site 4.

Hydrogeochemical Observations

Hydrochemical data derived from water quality tests performed on samples collected during the Bore-charger implementation and after the study are compared to understand the role of induced recharge on the quality of borewell water. Water samples were collected from six borewells, three dug wells, and two surface water bodies. Tables 12 and 13 present four tested parameters for each source before implementation, were assessed across all samples.

Pre-implementation pH values for all samples range between 7.8 to 8.25, TDS values are between 363 to 1220 mg/l, EC values 542 to 1820 $\mu\text{S cm}^{-1}$ and, Total Hardness ranges of 96 to 890 mg/l.

Post-implementation at the end of the impact study the pH values for all the samples were between 7.7 to 8.15, TDS values were in the range of 341 to 1243 mg/l, EC values were 509 to 1855 $\mu\text{S cm}^{-1}$, Total Hardness between a range of 91 to 785 mg/l.

Water Level & Water Quality Analysis

A) Water Level Observations at BW1, BW2, and Reservoir 1

- Figure 11(a) presents a graph indicating the comparative water levels in Borewells BW1, BW2, and Reservoir 1. The graph shows that there has been little to no change in the reservoir water level from October to December. This year, the rainfall in the region has been significantly above normal, which is reflected in the continuous base flows in the streams. As a result, the reservoirs created on these streams through check dams are full.
- BW1 and BW2 are located near Reservoir 1. The approximate distance between Reservoir 1 and BW1 is 25 meters, while the distance between Reservoir 1 and BW2 is 5 meters.
- Additionally, the distance between BW1 and BW2 is about 30 meters.
- BW2 is the borewell where the Bore-charger is implemented, BW1 serves as the observation borewell.
- The overall water levels in both borewells are notably high, almost reaching the surface. On November 28, 2023.
- BW2 experienced a significant drop in water level, which can be attributed to the mechanical lowering of the water level due to pumping activities associated with the Bore-charger operation (Fig. 14).

- However, after implementing the Bore-charger, the water level in the borewell begins to recover quickly, returning to its pre-implementation levels. This recovery indicates the positive impact of the Bore-charger recharging technique.
- Throughout this period, there has been minimal change in the reservoir water level.

From mid-January to the end of March, there is a gradual decrease in the surface reservoir levels. This decline is natural, considering the rates of evaporation and infiltration.

1. BW1, a non-implemented borewell, shows the maximum decline in water level. This may be attributed to its usage as a pumping well, as it does not receive recharge from the unconfined aquifer.
2. In contrast, BW2, a Bore-charger-implemented borewell, also functions as a pumping well but experiences a smaller decline in water level compared to BW1. This behavior may be due to the continuous induced recharge from the shallow unconfined aquifer, which helps maintain its water level. This observation highlights the positive impact of the Bore-charger technique on the recharging of borewells.

B) Water Level observations at BW3, DW1, DW2 & BW4.

Figure 11(b) compares water levels in borewells BW3, BW4, and dug wells DW1 and DW2.

1. BW3 is located near dug wells DW1 and DW2, with an approximate distance of 30 meters between them. The distance between BW3 and BW4 is around 100 meters.
2. BW3 is the borewell undergoing Bore-charger implementation, while BW4 is an observation borewell.
3. On November 28, 2023, BW3 experienced a temporary drop in water level, due to mechanical lowering due to pumping activities carried out for the Bore-charger operation.
4. After the implementation, BW3 began to recover, returning to its pre-implementation water level.
5. Throughout this period, there were hardly any observable changes in the water levels of the nearby dugwells DW1 and DW2.
6. By the end of January, the water level in the pumping borewell BW3 dropped below that of the observation borewell BW4, which is not actively being pumped and shows natural water level fluctuations.
7. Overall, there has been a gradual decrease in the water level of BW4. By the end of March, both the pumping (BW3) and observation (BW4) borewells exhibited similar water levels, while the water levels in dugwells DW1 and DW2 remained comparatively higher than in the borewells.
8. As a baseline, BW3 and BW4 showed relatively similar behavior patterns in their water levels. After BW3 was BoreCharged, is recharged from the unconfined aquifers where DW1 and DW2 are located, leading to similar and closer water level patterns between BW3 and the dugwells.
9. Following the BoreCharging of BW3, the water level difference between BW3 and BW4 noticeably increased as the season progressed, as BW4 did not receive the artificial recharge that BW3 did.

C) Water Level observations at BW5 & DW3

Figure 11(c) illustrates the comparative water levels in Borewells BW5 and DW3. The graph indicates that the dug well's water level changes little to no from October to December. This year, the region's rainfall has significantly exceeded normal levels, which can be observed through the sustained base flows in the streams. BW5 is located approximately 5 meters from Dugwell DW3.

1. BW5 is the borewell being utilized for the Bore-charger implementation, while DW3 serves as the observation dugwell.

2. Throughout most of the observation period, water levels in both wells remained high, almost near the surface.
3. However, after mid-December, the water level in the dug well began to drop due to its use for irrigation purposes.
4. A significant drop in the observation level of BW5 was recorded on November 27, 2023. This decline is attributed to the mechanical lowering of the water level caused by pumping activities related to the Bore-charger operation.
5. Following the implementation, the borewell began to recover and return to its pre-implementation level.
6. Since being BoreCharged, BW5 shows a gradual improvement in water levels. Notably, the water level in BW5 does not decrease significantly even with ongoing pumping for irrigation, which indicates a positive impact of the Bore-charger technique in maintaining a consistent supply of recharge water.
7. Moreover, there is no noticeable drop in the water level of DW3 following the Bore-charger implementation at BW5.
8. Both BW5 and DW3 exhibit similar patterns in water level changes after the Bore-charger implementation.

D) Water Level Observations at BW6 & Reservoir 2

Figure 11(d) compares water levels in Borewell BW6 and Reservoir 2. From the figure, it is evident that there has been little change in the reservoir water level during the months from October to December. Rainfall in the region was above normal, evident through the sustained base flows in the streams. BW6 is located close to Reservoir 2, approximately 5 meters away.

1. BW6 is the borewell where the Bore-charger implementation is being carried out, while the reservoir is the open surface water body under observation.
2. For most of the observation period, the overall water levels in both the borewell and the reservoir have been relatively high, nearly at the surface.
3. On 27 November 2023, BW6 experienced a significant drop in water level, which can be attributed to mechanical water extraction due to pumping activities for the Bore-charger operation.
4. Following the implementation, the borewell quickly began to recover and returned to its pre-implementation water level.
5. Throughout this period, there have been hardly any observable changes in the water level of the nearby reservoir.
6. The reservoir levels have remained stable over an extended time, while the water level in BW6 had shown some decline prior to the Bore-charger implementation.
7. Notably, the water level in BW6 has not significantly decreased, even with ongoing pumping for irrigation.

Site 1 Conclusion:

1. Despite a significant amount of recharge occurring in borewell BW2, which utilizes the Bore-charger technology, there is minimal impact on the water level in the neighboring reservoir.
2. This indicates that the implementation of Bore-charger does not negatively affect nearby surface water bodies.
3. In comparison to control BW1, the water level in BW2 is better maintained due to the induced recharge from Bore-charger operations.

4. Thus, Bore-charger-implemented borewell BW2 demonstrates superior performance over the control borewell BW1, thanks to its continuous recharge, making the Bore-charger technique an effective solution.

Site 2 Conclusion:

1. Seasonal changes, evaporative losses, evapotranspiration, and groundwater pumping for irrigation have contributed to a gradual decline in water levels in dug wells DW1 and DW2.
2. However, there has been no noticeable drop in the water levels of these wells due to the activities carried out on borewell BW3 with Bore-charger technology.
3. BW3 exhibits a similar potentiometric surface profile to DW1 and DW2, contrasting sharply with the behavior of BW4, indicating the success of Bore-charger-induced recharge.

Site 3 Conclusion:

1. Seasonal changes, environmental losses, and irrigation pumping have also led to a gradual decline in the water level of dug well DW3.
2. Therefore, there is no significant impact on DW3 due to the implementation of Bore-charger.
3. Post-implementation, borewell BW5 shows a similar potentiometric surface profile to DW3, suggesting that Bore-charger-induced recharge has been successful without adversely affecting the water levels in DW3.

Site 4 Conclusion:

1. The past monsoon season experienced heavy rains, and the lift irrigation scheme pumped significant amounts of water into the upstream areas of Aquifer 2. As a result, there has been substantial recharge in the upstream reservoir areas, keeping the base flow from the reservoir relatively unchanged until March.
2. Borewell BW6, a BoreCharged bore well, has been successfully recharged by the unconfined aquifer fed by the neighboring reservoir.
3. No decrease in the level of water in the reservoir following the implementation of Bore-charger, indicating no negative impact on the reservoir and suggesting a positive impact of the Bore-charger technique.
4. Overall, current observations and data analysis indicate that Bore-charger activity does not negatively affect nearby dug wells, borewells, or surface water bodies.
5. Water level data shows that, despite being used for pumping, Bore-charger-implemented borewells can maintain water levels until the end of March.

Conclusion

This study provides reassurance regarding the impacts of Bore-charger activity on surrounding water sources critical for agricultural irrigation. It suggests that Bore-charger implementation does not exacerbate water scarcity or compromise the availability of water for agricultural purposes. Furthermore, the capability of Bore-charger-implemented borewells to sustain water levels during pumping activities until the end of March highlights the technology's effectiveness in maintaining groundwater levels. This extended period of water availability is particularly important for agricultural irrigation during high-demand summer months. Overall, the findings emphasize the potential of Bore-charger technology to enhance the sustainability of agricultural irrigation by maintaining groundwater levels, minimizing adverse impacts on nearby water sources, and ensuring a reliable water supply for farming activities. The study offers valuable insights into the positive contributions of Bore-charger implementation to agricultural water management, thereby enhancing irrigation sustainability. Additionally, water quality parameters show a slight improvement in the quality of water in Bore-

charger-implemented borewells during the limited observation period. Over an extended recharge period, these improvements could become significant.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the Vinit Phadnis, Rahul Bakare and Ashwini Supekar used [Grammarly] in order to [Enhance the language]. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Competing Interests Declaration

All authors declare that they have no competing interests as defined by Elsevier, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

- **Conflict of interest:** The authors declare no conflict of interest.
- **Funding Declaration:** The authors declare that no funding, grant, or other support was received during the preparation of this manuscript
- **Financial Interests:** The authors have no relevant financial or non-financial interest to disclose
- Word count: 4976 words

Ethical Approval

The authors of "**Assess & Evaluate Impact of Bore-charger Activity on Nearby Water Bodies: A Case Study of Khalad, Purandar, Maharashtra India**", hereby declare that all authors have read, understood, and complied, as applicable, with the statement "Ethical Responsibilities of Authors" as found in the Instructions for Authors provided by Journal. Authors have read all the ethical responsibilities related to submission of a manuscript and there is no objection. We are affirming our commitment to upholding the highest standards of integrity and ethics in our research and publication practices.

Author Contribution Declaration

“All authors contributed to the study conception and design. Material preparation was performed by (Vinit Phadnis and Rahul Bakare) and further data generation and analysis were performed by (Vinit Phadnis and Ashwini Supekar). The first draft of the manuscript was written by (Vinit Phadnis, Rahul Bakare and Ashwini Supekar) and (Ashwini Supekar) reviewed the manuscript further all authors commented on a previous version of the manuscript. All authors read and approved the final manuscript”

Financial Interests Declaration

The authors declare they have no financial interest

Data Availability

- No/Not applicable (This manuscript does not report data generation or analysis).

Consent to Participate:

Participant understands their nature as a participant and that they consent to participate voluntarily.

References

- Annon, Anonymous, water- A shared responsibility, United Nation World Water Department Report. (2006)
- CGWB (2017) Aquifer mapping report, Purandhar & Baramati Tehsil of Pune District Maharashtra
- Deshmukh, S.S., (1988) Petrographic variations in compound flows of Deccan Traps and their significance, in Subbarao, K.V. ed. Deccan flood basalts; Bangalore Geological Society of India Memoir 10. pp.305 to 319.

- Godbole, S.M., Rana, R.S., Natu, S.R., (1996) Lava stratigraphy of Deccan basalts of western Maharashtra. Gondwana Geological Magazine Special Publication 2, 125–134.
- Kale.,V.S. & Kulkarni, H.C. (1992) IRS 1A and LANDSAT data n mapping Deccan Trap Flows around Pune, India : Implications on hydrogeological modeling ,ISPRS, pp 429-435.
- Kulkarni, H., et al., (2000) Hydrogeological framework of Deccan basalt ground water systems,west-central India. Hydrogeology Journal, 8 (4), 368–378.
- Macdonald, D.M.J., et al., (1995) Sustainable groundwater development of hard-rock aquifers: the possible conflict between irrigation and drinking water supplies from the Deccan basalts of India. Technical Report WC/95/52, British Geological Survey (NERC), Wallingford, UK.
- Millennium Developments Gols Report-2011' (MDG) target date of 2015 (UN 2011), Global HIV/AIDS response: epidemic update and health sector progress towards universal access: progress report 2011
- Narayan Hegde, BAIF, India's demand for water is growing strategies and security in India Indian Science Congress 2012
- Narayan Hegde et.al, BAIF Indian Science Congress 2012
- Subbarao K V and Hooper P R (1988) Reconnaissance map of the Deccan Basalt Group in the Western Ghats, India; In: Deccan Flood Basalts, (ed) K V Subbarao, Mem. Geol. Soc. India 10.
- UN-Water, United Nations World Water Development Report, 2006

Figures

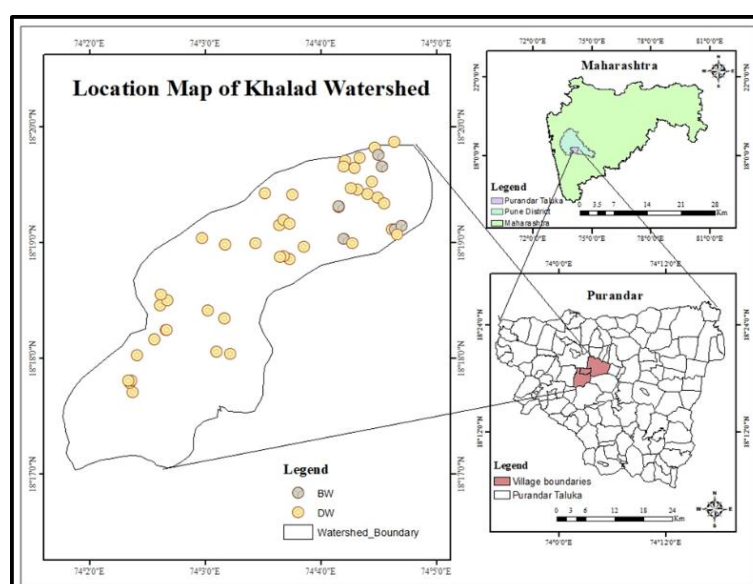


Fig.1: Location Map of the study area

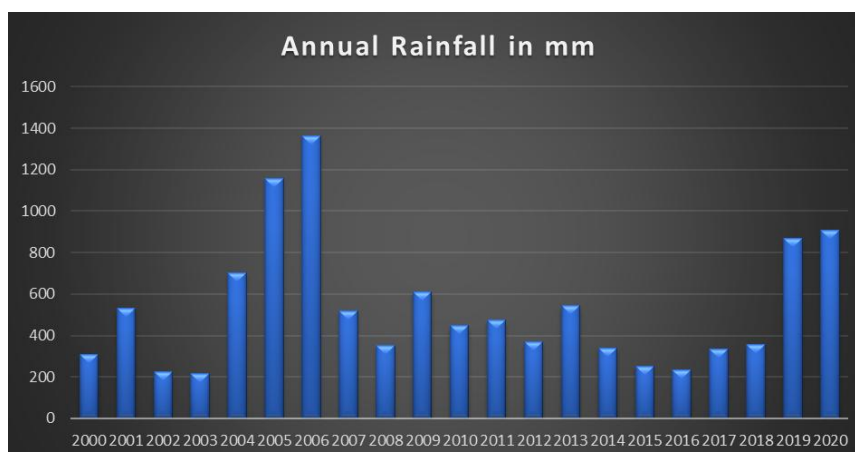


Figure 2: Annual rainfall

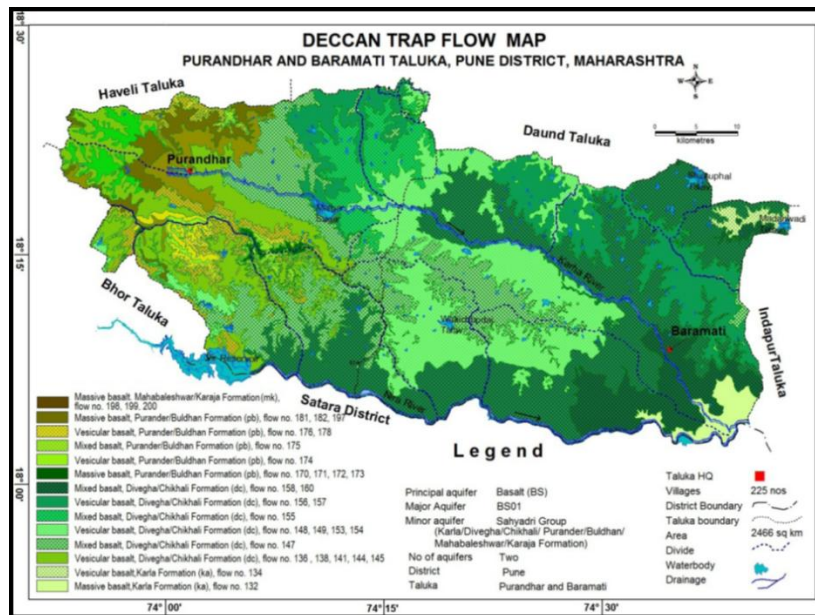


Figure 3: Deccan volcanic Province Map of Purandhar Taluka, Pune District, Maharashtra in India (Reference CGWB 2017)



Plate 1: Weathered Compact basalt



Plate 2: Vesicular Amygdaloidal Basalt unit

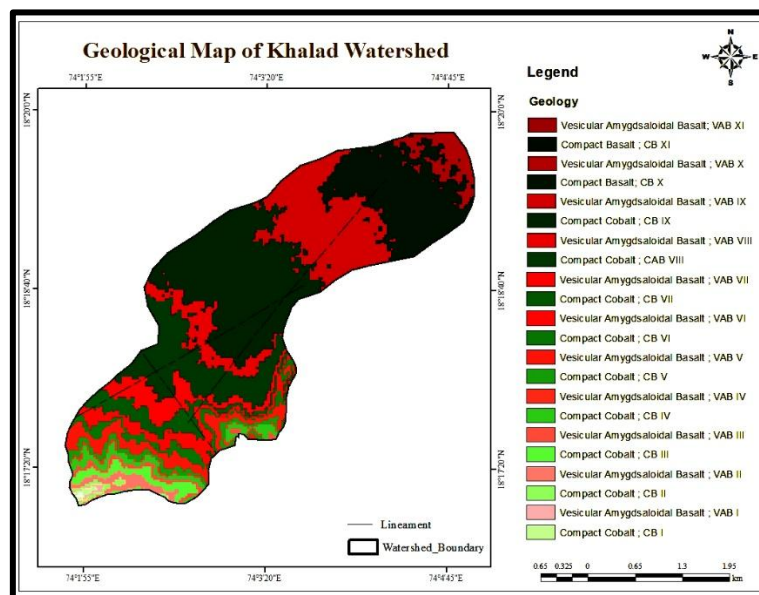


Figure 4: Geological Map of Khalad Watershed

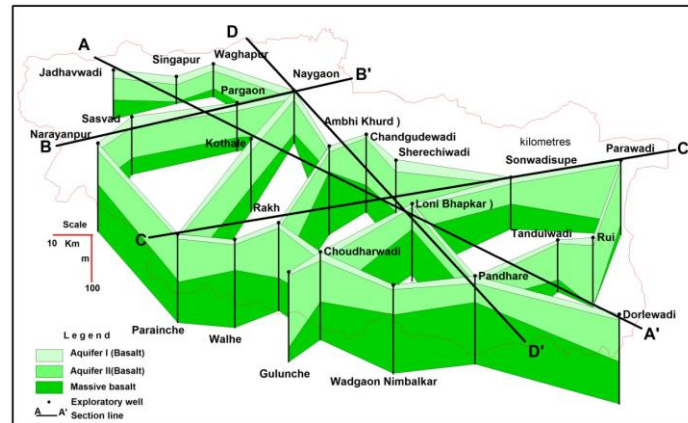


Figure 5: 3 D Fence Diagram indicating Aquifer Map of Purandhar & Baramati Taluka, Pune District, Maharashtra in India (Reference CGWB 2017)

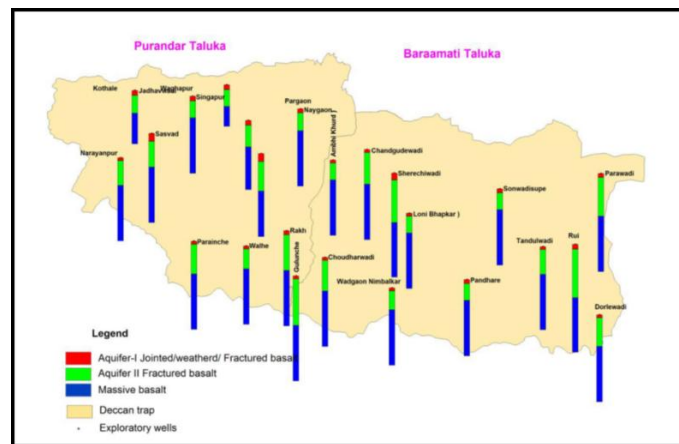


Figure 6: Subsurface Aquifer disposition based on lithology, Purandhar and Baramati taluka, Pune district (Reference CGWB 2017)

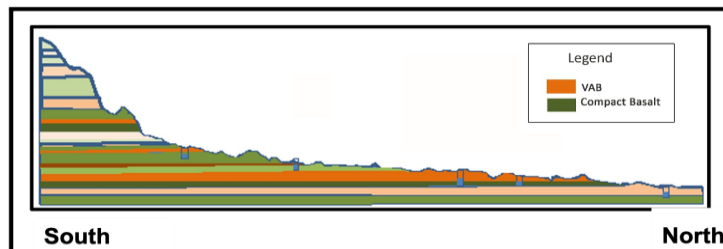


Figure 7: Conceptualize cross-section of Khalad Watershed

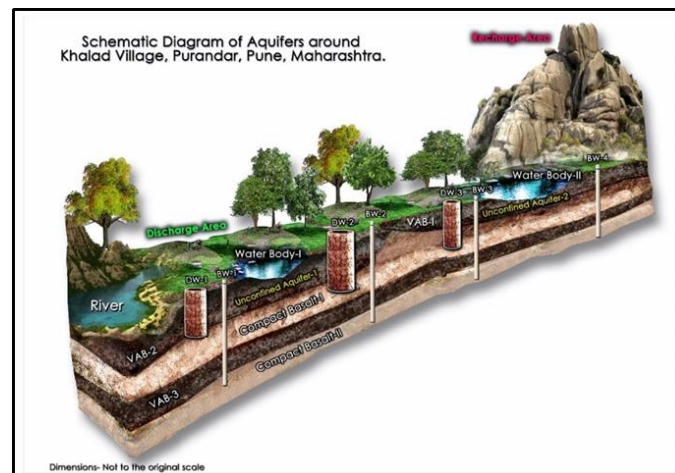


Figure 8: Three-dimensional conceptual model of Khalad watershed

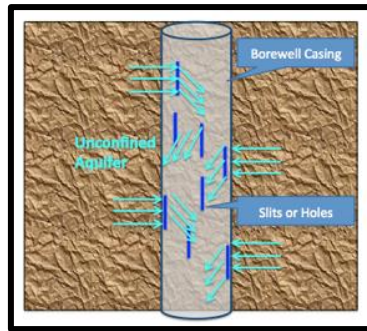


Figure 9: Schematic depicting Bore-charger Activity

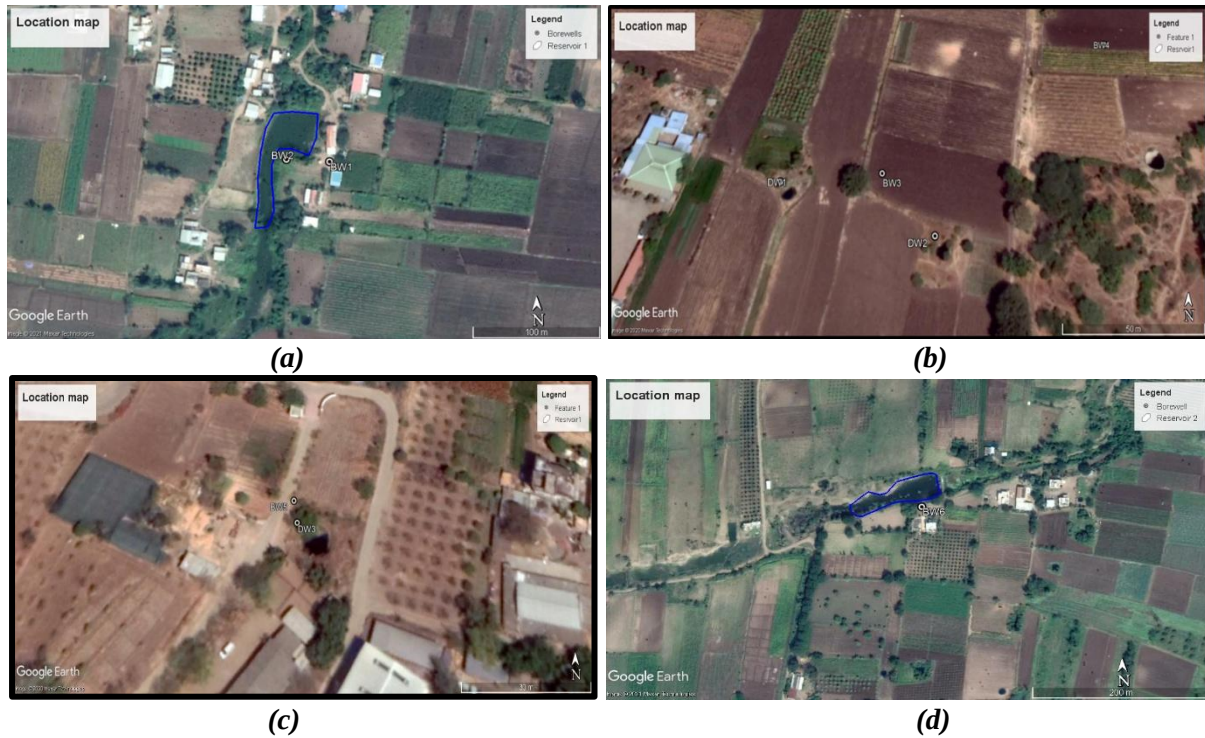


Fig. 10: (a)Location map of BW2; (b)Location map of BW3;(c)Location map of BW5; (d)Location map of BW6

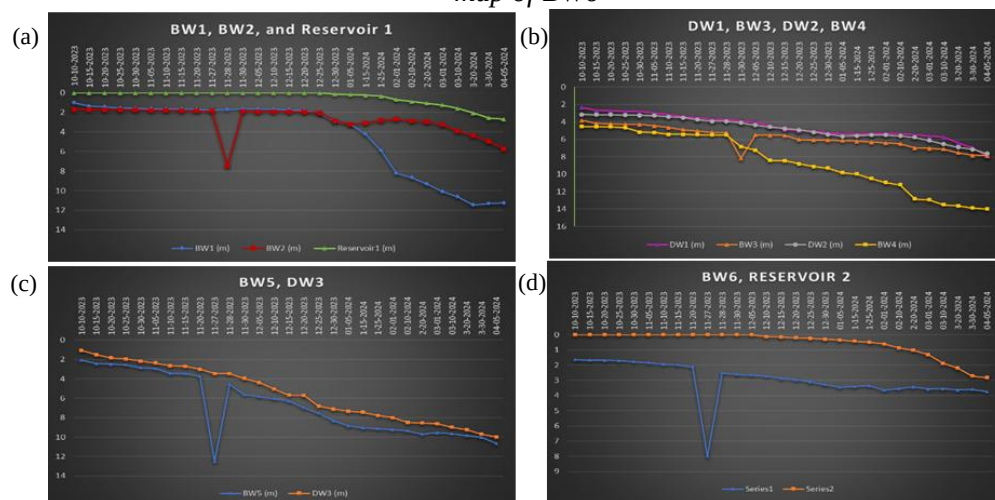


Figure 11: (a)Graph indicating the comparative water levels in Borewells BW1, BW2 & Reservoir1; (b)Graph indicating the comparative water levels in Borewells BW3, BW4 & Dugwells DW1 & DW2; (c)Graph indicating the comparative water levels in Borewells BW5 & DW3; (d)Graph indicating the comparative water levels in Borewells BW6 & Reservoir

Tables

Table No. 1: Highlights the water usage in India, Africa, Europe, and the world

Usage in %	World	Europe	Africa	India
Agriculture	69	33	88	83
Industrial	23	54	05	12
Domestic	08	13	7	05

Table No. 2: Future water usage (Source- Narayan Hegde, 2012)

Year	Agriculture	Industry	Domestic	Per Capita
INDIA	Billion liters/day			Liters/day
2000	1658	115	93	88.9
2050	1745	441	227	167
CHINA				
2000	1024	392	105	82.7
2050	1151	822	219	155.4
USA				
2000	542	605	166	582.7
2050	315	665	187	486.6

Table 3: Climatological Information for Purandhar- (2000-2023)

Year	Annual Rainfall (mm)
2000	310
2001	529.6
2002	223.4
2003	215
2004	700
2005	1158
2006	1365
2007	519
2008	350
2009	611
2010	448
2011	475.4
2012	371
2013	543.8
2014	339.8
2015	251.9
2016	234.3
2017	333.8
2018	358
2019	869
2023	906

Table 4: Details of selected Borewells for Observations

Site	Aquifer	Borewell Code	Name of the client	Location	Co-ordinates	Use
Site 1	Aquifer 1	BW1	Ganesh Raskar	Near Waterbody	18°19'39.60"N 74° 4'31.40"E	Observation Borewell
		BW2	Ganesh Raskar	Near Waterbody	18°19'39.53"N 74° 4'30.54"E	Bore-charger implemented

Table 5: Details of Observation Well Site 1

Borewell Number	Borewell Location	Borewell use	Depth of Casing pipe(m)	Observed SWL(m)	Borewell depth(m)	Depth of Slits (m)	No of Slits (No.)	Intervals between slits (m)
BW 2	18°19'39.6"N 74°04'31.4"E	Domestic/ Agriculture	6	7.5	76	3.5-6	12	0.5
Lithology:			Radius of Influence				100m	
Casing: 6m			Depth of Aquifer				6m	
Weathered Compact basalt: 6-10m			Rainfall				0.7m	
Fractured compact Basalt: 10-21.5m			Possible Recharge of Deeper Aquifer through Bore-charger				3014.4 cu. m	
Caving in Compact Basalt: 21.5-22m			Possible Recharge of Deeper Aquifer through the natural process				113.04 cu. m	
Vesicular Amygdaloidal Basalt: 22- 39.4 m								
Compact Basalt: 39.4- 52 m								
Vesicular Amygdaloidal Basalt: 52-76 m								
Caving in Vesicular Amygdaloidal Basalt:73.2 m- 74 m								
End: 76 m								

Table 6: Details of Borewell for Site 2

Site	Aquifer	Borewell Code	Name of the client	Location	Co-ordinates	Use
Site 2	Aquifer 1	BW3	Mohan Raskar	In between two dug wells	18°19'7.10"N 74° 4'38.30"E	Bore-charger implemented
		BW4	Mohan Raskar	At around 100 m from BW3	18°19'8.97"N 74° 4'41.70"E	Observation Borewell

Table 7: Details of Site 2

Borewell Number	Borewell Location	Borewell use	Depth of Casing pipe(m)	Observed SWL (m)	Borewell depth (m)	Depth of Slits (m)	No of Slits (No.)	Intervals between slits (m)
BW 3	18°19'02.1"N 74°04'11.5"E	Domestic/ Agriculture	6	8.5	96	6-3.5	13	0.5
Lithology			Radius of Influence				100m	
Casing : 6m			Depth of Aquifer				6m	
Weathered Compact Basalt: 6-12m			Rainfall				0.7m	
Fractured in compact Basalt: 12-26m			Possible Recharge of Deeper Aquifer through Borecharger				3014.4 cu.m	
Caving in compact Basalt: 35-35.5m			Possible Recharge of Deeper Aquifer through natural process				113.04 cu.m	
Vesicular Amygdaloidal Basalt: 26-56m			Radius of Influence				100 m	
Compact Basalt:56-74.4m			Depth of Aquifer				6m	
Vesicular Amygdaloidal Basalt:74.4-96m			Rainfall				0.7m	
End: 96m			Possible Recharge of Deeper Aquifer through Borecharger				3014.4 cu.m	
			Possible Recharge of Deeper Aquifer through natural process				113.04 cu.m	

Table 8: Details of Borewell for Site 3

Site	Aquifer	Borewell Code	Name of the client	Location	Co-ordinates	Use
Site 3	Aquifer 2	BW5	Gram Gaurav Pratishthan	Near Dugwell	18°19'18.80"N 74° 4'9.10"E	Bore-charger implemented

Table 9: Details of site 3

Borewell Number	Borewell Location	Borewell use	Depth of Casing pipe (m)	Observed SWL(m)	Borewell depth(m)	Depth of Slits (m)	No of Slits (No.)	Intervals between slits (m)
BW 5	18°19'07.1"N 74°04'38.3"E	Domestic/ Agricultur e	6	11	66	6-4	10	0.5
Lithology			Radius of Influence				100 m	
Casing: 6m			Depth of Aquifer				6m	
Fractured Compact Basalt: 6-18.5m			Rainfall				0.7m	
Vesicular AmygdaoidalBasalt:18.5-44m			Possible Recharge of Deeper Aquifer through Borecharger				3014.4 cu.m	
Compact Basalt: 44-50.3m			Possible Recharge of Deeper Aquifer through natural process				113.04 cu.m	
Vesicular AmygdaoidalBasalt:50.3-66m								
Caving in Vesicular Amygdaloidal Basalt: 63.1-64m								
End : 66m								

Table 10: Details of Borewell for Site 4

Site	Aquifer	Borewell Code	Name of the client	Location	Co-ordinates	Use
Site 4	Aquifer 1	BW6	Suresh Raskar	Near Waterbody	18°19'2.10"N 74° 4'11.50"E	Bore-charger implemented

Table 11: Details of site 4

Borewell Number	Borewell Location	Borewell use	Depth of Casing pipe(m)	Observed SWL(m)	Borewell depth (m)	Depth of Slits (m)	No of Slits (No.)	Intervals between slits (m)
BW 6	18°19'45.6"N 74°04'29.6"E	Domestic/ Agriculture	6	8	71	3.5-6	12	0.5
Lithology			Radius of Influence				100 m	
Casing: 6m			Depth of Aquifer				6 m	
Weathered Compact Basalt: 6-11.5m			Rainfall				0.7 m	
Fractured compact Basalt: 11.5-26m			Possible Recharge of Deeper Aquifer through Borecharger				3014.4 cu. m	
Red Bole :26-26.8m			Possible Recharge of Deeper Aquifer through natural process				113.04 cu. m	
Vesicular Amygdaloidal Basalt:26.8-42m								
Compact Basalt:42-55.7m								
Red Bole :55.7-57m								
Vesicular Amygdaloidal Basalt:57-71								
End: 71m								

Table 12: Water quality parameters before Bore-charger implementation.

WELL ID	BW1 (m)	BW2 (m)	BW3 (m)	BW4 (m)	BW5 (m)	BW6 (m)	DW1 (m)	DW2 (m)	DW3 (m)	Reser voir1 (m)	Reser voir2 (m)
pH	8.12	7.93	7.85	8.25	7.8	7.9	8.1	8.1	8.2	7.9	7.8
TDS	610	714	363	1220	754	1174	950	660	625	1120	1085
EC	910	1065	542	1820	1125	1752	1418	1015	977	1671	1619
Total Hardness	490	405	266	890	477	96	86.4	160	132	238	189

Table 13: Water quality parameters after Bore-charger implementation

WELL ID	BW1 (m)	BW2 (m)	BW3 (m)	BW4 (m)	BW5 (m)	BW6 (m)	DW1 (m)	DW2 (m)	DW3 (m)	Reser voir1 (m)	Reser voir2 (m)
pH	8.1	7.96	7.75	8.15	7.7	7.78	8.2	8.15	8.15	8.1	8.02
TDS	620	655	341	1235	628	1071	965	684	639	1243	1136
EC	925	971	509	1843	937	1599	1440	1021	953	1855	1695
Total Hardness	478	197	142	785	312	91	94.5	178	127	264	204



Understanding the Hydrodynamics of parts of Araria District, Bihar using Geospatial Technique

Anugya Rashi, Anil Kumar, Bhavuk Sharma

Department of Geology, Patna University, Ashok Rajpath, Patna-800005

E-mail: ashipriya451@gmail.com

Abstract

Groundwater is the earth's most valuable natural resource. It is widely used for drinking and irrigation purposes worldwide. Changing climatic conditions influence hydrogeological processes, whose effect can also be seen in the northern parts of Bihar. Hence, understanding the dynamics of the region's water resources in the context of rising water demand and climate unpredictability requires a hydrogeological study, and we have studied the areas in and around the Araria district of North Bihar. In our study, we have used geospatial tools like geographical information system and remote sensing images, which have been further processed to develop the study area's slope and drainage density map. This has helped us to analyze hydrological features, terrain variability, and surface runoff. The value of the slope ranges from 0° (low) to 3.83° (medium) and 15.48° (high) and is found to be directed toward the central part of Bihar. The range of drainage densities, which represents variations in water flow and infiltration capability, varies from 0 to 343.365 km/km^2 . The topography is gentler in lower slope locations where water can accumulate and create dense stream networks, increasing surface runoff and resulting in a higher drainage density. The quick water flow in steeper areas, on the other hand, limits stream development and reduces infiltration, leading to concentrated flow routes and a decreased drainage density. Therefore, these maps offer vital information about the region's surface dynamics, which helps us comprehend drainage patterns, slope variations, and how they affect erosion and groundwater recharge.

Keywords: Groundwater, Remote Sensing, GIS, Slope, Drainage Density, Bihar

Introduction

Throughout the world, groundwater is an essential resource for home, industrial, and agricultural operations. India, the world's largest agricultural consumer of groundwater, has witnessed a revolutionary transition from extensive surface water management to widespread groundwater extraction (Srivastava et al. 2012). According to the reports of Dimitris Dermatas 2017 additionally, the tenth aim of SDG 3, which is to significantly reduce the number of deaths and illnesses by 2030, centers on water and soil pollution. The SDGs, sometimes known as the "nexus approach," represent an inclusive, integrated approach to global development that aims for environmental sustainability and human well-being (Griggs et al. 2013, 2014; Boas et al. 2016; Stafford-Smith et al. 2016; Gupta and Vegelin 2016).

Open well water as a groundwater source was deemed safe for drinking water before the 1980s, but in recent years, the Gangetic plains have seen a multiplication of arsenic pollution due to increased anthropogenic activity and geogenic causes (Kumar et al. 2021). According to Babar A Shah (2007), the polluted aquifers in the Terai area of Nepal are very similar in nature and age to those of the Middle Ganga Plain (MGP). The MGP sediments are primarily from the Himalayas, with modest contributions from Peninsular India.

Competition for water resources is predicted to intensify due to population expansion, urbanization, and climate change, with a specific effect on agriculture. By 2050, the population is predicted to reach over 10 billion people, and to meet their fundamental needs, both urban and rural populations will require food and fiber. Despite its reputation as a water-efficient state, Bihar's composite water index score (CWIS) (FY 16–17), as calculated by NITI Ayog, is 38, showing that the state's water resources are not

being managed effectively. Appropriate management and groundwater quality research are necessary to improve the Composite water management index. According to the reports of the Central Ground Water Board (CGWB), which has conducted studies on Araria's groundwater resources as of 31 March, 2009, the net annual replenishable groundwater is estimated to be 803.97 million cubic metres with groundwater development of 31.9%, indicating a good amount of groundwater for future use. Also, the Araria District in northern Bihar is a groundwater-rich part of the Indo-Gangetic Plain, which was created by the dynamic fluvial system of the Kosi River. This study focuses on drainage densities, discharge changes, slope features, and river flow patterns. Additionally, the effects of drainage density and slope on the distribution of surface water and groundwater dynamics in the area are examined. The main objective of the study area: 1) To develop slope and drainage density maps using geospatial technique and examine their groundwater flow trends in Bihar's Araria district, 2) To examine how topography's impact on groundwater recharge and the study area's hydrogeological processes and 3) To evaluate geospatial analysis for flood mitigation and sustainable resource management for the region's future resilience.

Study Area

The study area (Fig.1) focuses on sediment deposition patterns, hydrodynamics, and groundwater evaluation to comprehend the river's influence on Araria's water resources and land use with a longitude Range of 86°50' E to 87°50' E and, latitude Range of 25°30' N to 26°30' N."

The Araria district in northeastern Bihar is included in the survey of India's toposheets 72N and 72O. Araria, which connects Nepal, Kishanganj, and Supaul, is a level area with mild elevations. Floodplain dynamics and frequent channel movements are caused by significant Himalayan sedimentation, even though the region is flat ground with fertile soils that are ideal for agriculture. Groundwater benefits from multiple aquifers with alternating zones of sand and clay. the region where the alluvial plains and foothill deposits of the Eastern Himalayas converge. Araria and the surrounding region are defined by the fluvial-alluvial geomorphology, dynamic river processes, and active surface–subsurface water interaction.

Araria has been greatly impacted by the Kosi River's historical westward migration brought on by geological activity and silt accumulation. Large floodplains are produced by monsoon floods, which replenish groundwater but also cause protracted waterlogging that affects human populations and agriculture. The area is perfect for researching the socio-environmental impacts of surface-subsurface water interactions.

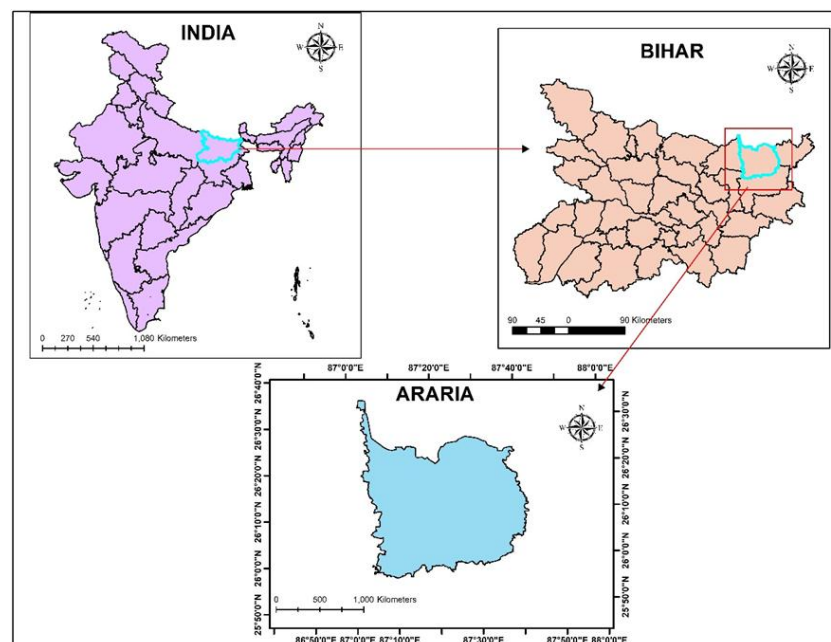


Fig.1 Study Area lies in the Northeastern part of Bihar

Materials and Methods

The study methodology (Fig. 2) incorporates three primary approaches: 1) data collection and processing 2) geospatial and remote sensing techniques 3) GIS map creation.

Data collection, processing, and topographic data extraction are done using the SRTM DEM1Arc second global pictures from USGS Earth Explorer that were downloaded on November 19, 2024 to illustrate the terrain.

Correcting any sinks or depressions in the DEM is used for precise hydrological modeling. Hydrological and terrain features are extracted utilizing remote sensing and geographic information system (GIS) approaches. Hydrological processing techniques include stream delineation, flow direction, and accumulation and for terrain analysis, slope variation and drainage pattern identification are employed.

Spatial analysis tools are used to create maps of drainage density and slope. GIS Tools Used Slope Tool (Spatial Analyst) takes DEM data and extracts slope values in degrees or percentages, helps in distinguishing steep and flat terrains. The flow direction tool (Hydrology Toolbox) determines the direction of water flow from each cell in the DEM. Flow Accumulation Tool (Toolbox for Hydrology) determines the total flow in the landscape, which helps identify stream networks. The Hydrology Toolbox's Stream Order Tool Classifies stream networks. Tool for Line Density (Spatial Analyst) calculates the number of streams per unit area to create a drainage density map. Hillshade Tool (3D Analyst) simulates light and shadow effects to improve the visualization of terrain.

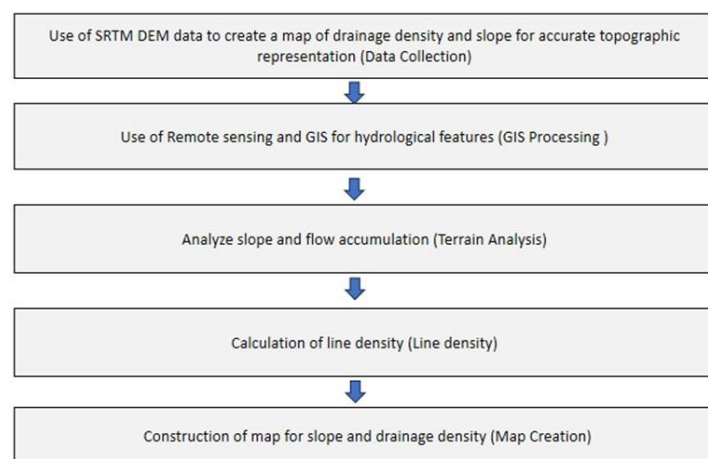


Fig.2 Represents the research methodology in the flowchart

Results and Discussion

Slope Analysis

Slope analysis is a technique for determining the degree of slope steepness and possible environmental impact by analyzing the change in terrain elevation across a given area determined in high, moderate, and steep slopes. A digital elevation model (DEM) with a spatial resolution of 30 meters was used to prepare the area's slopes. The slope of the research area was then divided into four classes (Table 1), as shown in Fig. 3, with the lowest and greatest values being 0–5 and 10–15°, respectively. The area's steep and level gradient significantly affects the presence and transportation of groundwater (Hussein et al 2017).

Slopes that are high and moderate allow runoff, which impacts groundwater recharge. The risk of erosion and landslides may be higher in steeper terrain. Although they are susceptible to water stagnation, low-slope areas are better suited for agriculture, habitation, and groundwater recharge. Moderate slope areas are best suited for varied land uses, but they also need erosion control measures. High-slope areas are better suited for forest protection but less ideal for development since they are more likely to experience landslides and soil erosion.

Table 1: Representing the slope classification and analysis

Slope ($^{\circ}$)	classification	Terrain characteristics	Agriculture/farming suitability	Erosion risk	Other uses
0-5 $^{\circ}$	Green	Very little slope, flat terrain, prone to water stagnation	Good for agriculture, settlement and habitation but flood risk can hinder agriculture	Little risk	used for agriculture and farming but flood risk management is necessary.
5-10 $^{\circ}$	Yellow	Moderate slopes	It may require terracing and contour farming to minimize erosion	Moderate risk	Suitable for agriculture and forestry but with precautions.
10-15 $^{\circ}$	Red	Steeper slopes	Less suited for and agriculture	High risk	Not suitable for agriculture and farming without modern agricultural techniques.

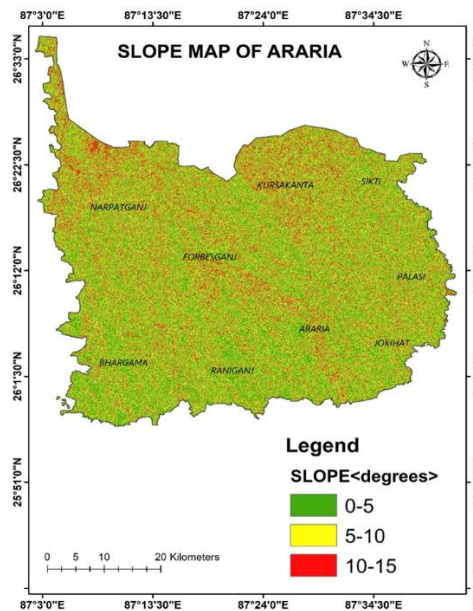


Fig.3 Slope map of the study area

Drainage Density analysis

A watershed's drainage density (Dd) indicates how well or badly stream channels drain it. It is calculated by dividing the total area of a particular area by the total length of its streams. Areas with varying stream concentrations are graphically represented on the Drainage Density Map (Fig. 4), which can reveal a range of hydrological and geomorphological features. Using GIS techniques, it is calculated by superimposing stream networks on the topography of a certain area. Generally, the density is divided into three categories (Table 2) =: (1) low drainage density (Green Area. (2) moderate drainage density (Yellow-Green Transition) (3) high drainage density (Red to Yellow on the map), which varies from 0 to 343.365 km/km².

Planning flood mitigation techniques, choosing agricultural locations, comprehending surface water distribution, and guaranteeing sustainable groundwater management are all made easier with this drainage density map of Araria.

This study also includes a connection between climate change and sustainable development goals. The study will help the researchers reach sustainable development goals in the context of a changing climate by outlining certain avenues for in-depth future research in water resource management (Dixit et al., 2022).

Table 2: Interpretation of Drainage Density and Its Implications

Drainage Density	Key Characteristics	Implications	Suitability for settlement and agriculture
Low Drainage Density area (Green areas)	Permeable soils, flatter terrain	Higher groundwater recharge potential	Suitable for agriculture, good water retention and settlement
	Fewer streams	Less erosion but has potential water stagnation	Suitable for infrastructure development
	Lower surface runoff	Higher potential for waterlogging, reduced erosion	
High Drainage Density area (Red areas)	higher rate of water flow	increased risk of flash floods	less suitable for habitation due to flood risks
	more streams, impermeable rocks, steeper slopes	higher surface runoff and erosion	less suitable for agriculture due to erosion and flash flood
	more active flow	lower groundwater recharge	

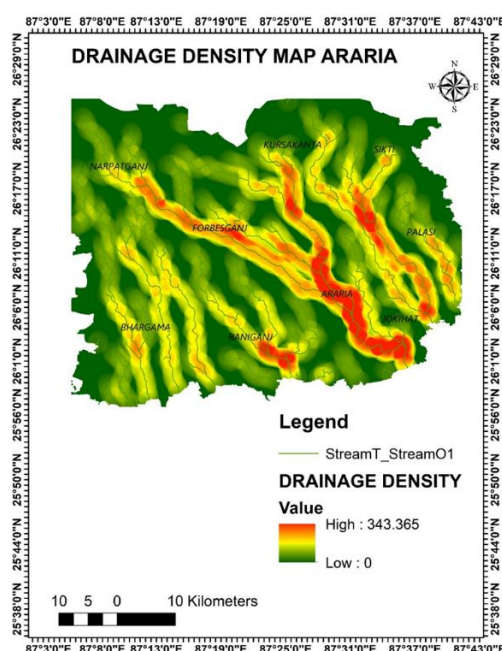


Fig.4 Drainage density of the study area

Conclusion

Araria district's drainage density and slope maps offer important information on the area's hydrological and geomorphological features. These maps are essential for managing land and water resources sustainably, especially regarding flood mitigation and groundwater development. According to the slope map, the majority of the Araria district has low to moderate slopes (0–5°), however, certain regions have high slopes (10–15°) and moderate slopes (5–10°). Low slopes indicate that the area is primarily a level alluvial plain, which is perfect for infrastructure development, groundwater recharge, and agriculture. while the greater slope areas might influence drainage patterns and flood susceptibility by increasing surface runoff.

The concentration and spread of streams throughout the area are shown on the drainage density map. While low drainage density (green zones) denotes improved groundwater recharge capacity, high

drainage density (red zones) indicates more surface runoff and less infiltration. Flash floods during the monsoon season may result from the presence of high drainage density areas, which are correlated with inadequate infiltration capacity. Areas with low drainage densities are crucial for the sustainable planning of water resources because they have more potential for groundwater recharge and storage.

By combining these maps, areas with low drainage densities and low slopes can be found to be the best places for artificial recharge systems, check dams, and percolation tanks, structures that recharge groundwater. Flood control measures, such as appropriate drainage channelization and embankment reinforcement, can be monitored in high drainage density zones. Finding appropriate sites for roads, crops, and settlements while avoiding high runoff zones that could cause erosion or waterlogging helps improve sustainable urban design.

References

ArcGIS 10.8 software

- Alam, M. G. M., Allinson, G., Stagnitti, F., Tanaka, A., & Westbrooke, M. (2002). Arsenic contamination in Bangladesh groundwater: a major environmental and social disaster. *International journal of environmental health research*, 12(3), 235-253.
- Bapalu, G. V., & Sinha, R. (2005). GIS in flood hazard mapping: a case study of Kosi River Basin, India. *GIS Development Weekly*, 1(13), 1-3
- Chakraborti, D., Mukherjee, S. C., Pati, S., Sengupta, M. K., Rahman, M. M., Chowdhury, U. K., ... & Basu, G. K. (2003). Arsenic groundwater contamination in Middle Ganga Plain, Bihar, India: a future danger?. *Environmental health perspectives*, 111(9), 1194-1201.
- cgwb.gov.in (Ground Water Information Booklet Araria District, Bihar State 2013)
- Chen, N. S., Hu, G. S., Deng, W., Khanal, N., Zhu, Y. H., & Han, D. (2013). On the water hazards in the trans-boundary Kosi River basin. *Natural Hazards and Earth System Sciences*, 13(3), 795-808.
- Dermatas, D. (2017). Waste management and research and the sustainable development goals: Focus on soil and groundwater pollution. *Waste Management & Research*, 35(5), 453-455.
- Dixit, A., Madhav, S., Mishra, R., Srivastav, A. L., & Garg, P. (2022). Impact of climate change on water resources, challenges and mitigation strategies to achieve sustainable development goals. *Arabian Journal of Geosciences*, 15(14), 1296.
- Hussein, A. A., Govindu, V., & Nigusse, A. G. M. (2017). Evaluation of groundwater potential using geospatial techniques. *Applied Water Science*, 7, 2447-2461.
- Kumar, A., Ali, M., Kumar, R., Kumar, M., Sagar, P., Pandey, R. K., ... & Ghosh, A. K. (2021). Arsenic exposure in Indo Gangetic plains of Bihar causing increased cancer risk. *Scientific reports*, 11(1), 2376.
- Neumann, R. B., Ashfaq, K. N., Badruzzaman, A. B. M., Ashraf Ali, M., Shoemaker, J. K., & Harvey, C. F. (2010). Anthropogenic influences on groundwater arsenic concentrations in Bangladesh. *Nature geoscience*, 3(1), 46-52.
- O'Keeffe, J., Buytaert, W., Mijic, A., Brozović, N., & Sinha, R. (2016). The use of semi-structured interviews for the characterisation of farmer irrigation practices. *Hydrology and Earth System Sciences*, 20(5), 1911-1924.
- Shah, B. A. (2008). Role of Quaternary stratigraphy on arsenic-contaminated groundwater from parts of Middle Ganga Plain, UP-Bihar, India. *Environmental Geology*, 53, 1553-1561.
- Sinha, R., Bapalu, G. V., Singh, L. K., & Rath, B. (2008). Flood risk analysis in the Kosi river basin, north Bihar using multi-parametric approach of analytical hierarchy process (AHP). *Journal of the Indian Society of Remote Sensing*, 36, 335-349.
- Sharma, Y., Kumari, M., Wadhwani, M. K., Sidana, B. K., Kumar, S., Panda, C. K., ... & Rahman, S. M. (2024). Untapped Potential of Groundwater Resources of Bihar. *Economic Affairs*, 69(2), 785-790.



Landslide Susceptibility Mapping in Western Ghats using AHP-Weighted Overlay Modelling: A Case Study of Patan Taluka, Satara, India

Amit Vijaykumar Shirke, Bhavana Umrikar

Department of Geology, Savitribai Phule Pune University, Pune- 411007, Maharashtra, India
E-mail: amitshirke2311@gmail.com

Abstract

The Western Ghats of Maharashtra are among the most landslide-prone mountain systems in India, owing to their steep escarpments, heavy monsoonal rainfall, structurally controlled basaltic geology, and rapidly evolving land-use patterns. This study employs an integrated geospatial approach to delineate landslide susceptibility zones in and around Patan Taluka of Satara District using the Analytical Hierarchy Process (AHP) and Weighted Overlay Analysis (WOA) within a GIS environment. Ten conditioning factors including slope, elevation, drainage density, distance to lineament, distance to road, topographic wetness index (TWI), rainfall, earthquake density, land use/land cover (LULC), and NDVI. The factors were derived from satellite datasets, field observations, and ancillary sources. Each factor was reclassified into susceptibility classes and assigned weights through pairwise comparison matrices using AHP, yielding a consistency ratio of 0.085, confirming the reliability of the weighting process. The weighted thematic layers were integrated to compute the Landslide Susceptibility Index (LSI), resulting in four susceptibility categories: Very High, High, Moderate, and Low. Approximately 34% of the study area falls under High to Very High susceptibility zones, primarily along the western escarpment and structurally weakened regions near *Mirgaon*, *Koyananagar*, *Rasati*, *Miraswadi*, *Ambeghar*, and the *Karad–Chiplun corridor*. Moderate susceptibility covers 48% of the landscape, while 18% exhibits Low susceptibility. Model validation using historical landslide records and field observations confirms strong agreement with mapped high-risk zones. The findings demonstrate the effectiveness of the AHP–WOA framework for landslide hazard assessment in complex volcanic terrains such as the Western Ghats. The resulting susceptibility map serves as a key decision-support tool for slope management, infrastructure development, and disaster risk reduction in vulnerable communities.

Keywords: Landslide Susceptible Zones; Western Ghats; Weighted Overlay Analysis, AHP

Introduction

Landslides are among the most devastating geomorphic hazards in mountainous regions, especially where steep terrain, intense rainfall, and fragile lithological conditions converge. A landslide is generally defined as the downslope movement of rock, soil, or debris driven by gravity, typically along shear zones or pre-existing structural weaknesses (Cruden & Varnes, 1992). These mass movements can result in severe damage to human life, transportation networks, agricultural land, ecological systems, and socio-economic infrastructure. Globally, thousands of slope failures are recorded each year, with developing countries experiencing disproportionately high impacts due to rapid land-use changes and unregulated expansion of infrastructure in unstable terrains (Froude & Petley, 2018). India is among the most landslide-prone nations in the world, with nearly 450,000 km²—constituting approximately 15% of its landmass—classified as highly susceptible to landsliding (GSI, 2009). The Western Ghats form a prominent high-risk zone due to their steep escarpments, deeply incised valleys, lateritic capping, and structurally controlled Deccan volcanic geology. The region receives exceptionally high monsoonal rainfall, which contributes to pore-pressure buildup, soil saturation, and rapid weathering, increasing the frequency of slope failures (Thigale & Khandge, 1996; Saha et al., 2023). In recent years, the Western Ghats of Maharashtra have witnessed repeated catastrophic

landslides, many of which are directly associated with anthropogenic activities—such as hill-cutting for roads, settlement expansion, deforestation, and poorly engineered slope modifications—that intensify naturally unstable conditions.

Patan Taluka in Satara District represents one of the most affected sectors within the Western Ghats. Recurring slope failures have been reported in and around villages such as Mirgaon, Miraswadi, Koyananagar, Rasati, Dhokawale, Mulgaon, and along the Karad–Chiplun road corridor, posing continuous threats to communities and critical transport infrastructure. Understanding the spatial distribution of landslide susceptibility in this area is therefore essential for risk mitigation, informed land-use planning, and sustainable development. Geospatial technologies provide robust capabilities for landslide susceptibility assessment by integrating remotely sensed datasets, topographic derivatives, and environmental parameters within a Geographic Information System (GIS). Multi-criteria decision-making techniques such as the Analytical Hierarchy Process (AHP) enable systematic and rational assignment of comparative weights to multiple landslide-conditioning factors (Saaty, 1980). When combined with Weighted Overlay Analysis (WOA), these weights can be spatially synthesized to identify the degree of susceptibility across a landscape with high precision (Yalcin, 2008; Shahabi & Hashim, 2015). Based on the geomorphic and climatological characteristics of the Western Ghats, the present study incorporates ten major conditioning factors—elevation, slope, drainage density, topographic wetness index (TWI), rainfall, NDVI, land use/land cover (LULC), distance to lineament, distance to road, and earthquake density—to quantify landslide susceptibility in Patan Taluka using an integrated AHP–WOA framework. The objective of the study is to generate a scientifically validated Landslide Susceptibility Map that can serve as a crucial decision-support tool for policymakers, engineers, and disaster management authorities. The resulting susceptibility zonation provides insights into high-risk areas that require immediate attention for mitigation planning, slope stabilization measures, and regulated developmental interventions in this environmentally fragile mountainous region.

Study area

The study area is located in Patan Taluka of Satara District, in the south-western part of Maharashtra, India. Geographically, it extends from 73°38'34.84"E to 74°04'06.83"E longitude and 17°31'18.55"N to 17°14'35.17"N latitude, covering an area of approximately 625 km². Patan lies within the central sector of the Western Ghats, a globally recognized biodiversity hotspot and UNESCO World Heritage Site. The region is marked by rugged topography, steep escarpments, deeply incised river valleys, structurally controlled plateaus, and discontinuous lateritic capping, creating a landscape that is highly sensitive to slope instability. The drainage network is well developed, with the *Koyana*, *Kera*, *Morna*, and *Varna* rivers and their tributaries carving through the elevated basaltic terrain and producing strong relief contrasts. Elevation varies between 543 m and 1137 m, with steeper and more dissected slopes concentrated in the western and south-western portions of the taluka. These high-altitude zones comprise duricrust–laterite formations and multi-tiered Deccan basalt flows, characterized by alternating permeable and impermeable layers, giving rise to perched aquifers, seepage zones and spring emergence. Such hydrogeological conditions are known to enhance slope instability along basalt–laterite interfaces (Saha et al., 2023). Patan Taluka receives intense monsoonal precipitation controlled by the orographic effect of the Western Ghats, with average annual rainfall ranging from 909 mm in the eastern plains to more than 4000 mm toward the western escarpment. Sustained heavy rainfall triggers multiple geomorphic processes including saturation-induced weakening of weathered basalt, increased pore-water pressure, accelerated runoff, and gullying—all of which contribute to landslide initiation. Historical evidence and field observations indicate recurring landslides in *Mirgaon*, *Miraswadi*, *Koyananagar*, *Ambeghar*, *Dhokawale*, *Mulgaon*, and along the Karad–Chiplun road, where road cutting and slope modification further aggravate geomorphic instability. The land use/land cover (LULC) pattern demonstrates sharp spatial variability. While dense forests dominate the western slopes and function as a stabilizing agent, agricultural land, plantations, and settlements are primarily concentrated in the mid-slope and eastern terrain. Reservoir-influenced regions associated with the Koyna hydroelectric project also experience periodic slope stresses due to fluctuating water levels and seismicity. Notably, infrastructural development and transportation corridors, particularly hill roads, have increased slope exposure and erosion, making distance to roads and distance to lineaments relevant

parameters for susceptibility modelling (Pourghasemi et al., 2012). Owing to the combination of steep slopes, heavy rainfall, structural discontinuities, seismic activity, anthropogenic modification, and heterogeneous land use, Patan Taluka presents ideal characteristics for landslide susceptibility assessment using geospatial and multi-criteria decision-making approaches. These environmental and geomorphic complexities justify the use of parameters such as elevation, slope, drainage density, TWI, rainfall, NDVI, LULC, distance to lineament, distance to road, and earthquake density in developing a spatially explicit landslide susceptibility model for the region.

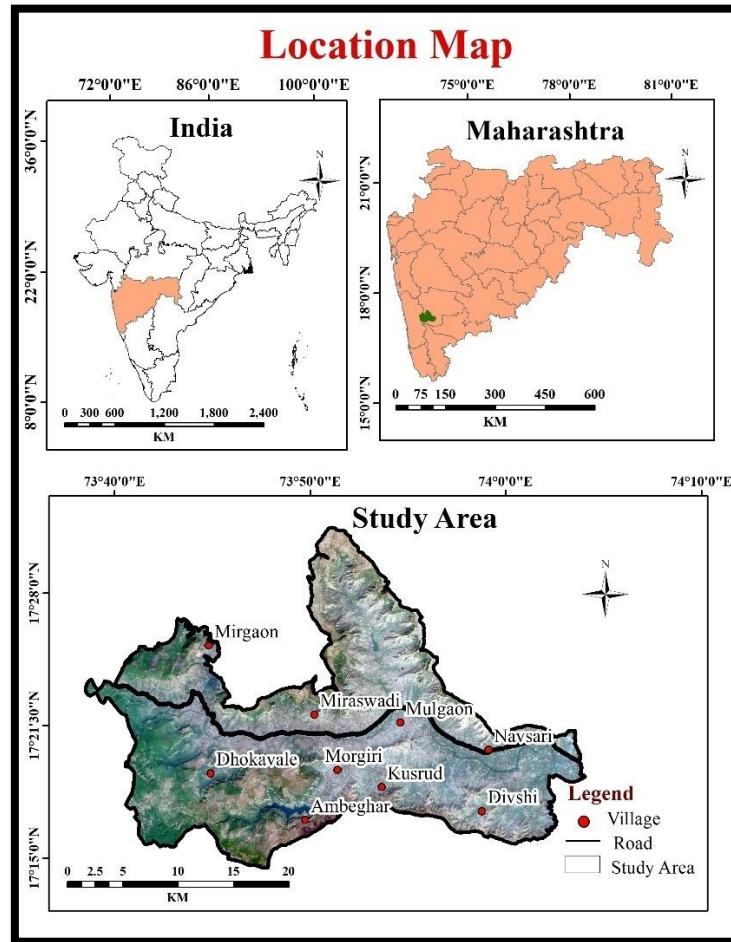


Figure 1: Location of the study area.

Materials and Methods

The methodological framework employed in this study integrates remote sensing datasets, thematic layer generation, multi-criteria decision-making, and geospatial overlay modelling to produce a Landslide Susceptibility Map (LSM) for Patan Taluka. The overall workflow consists of four sequential stages: (i) acquisition and preparation of thematic layers, (ii) reclassification and normalization of conditioning factors, (iii) computation of factor weights using the Analytical Hierarchy Process (AHP), and (iv) integration of weighted factors through Weighted Overlay Analysis (WOA) in a GIS environment. This combined AHP–WOA approach is widely regarded as a robust method for representing the physical complexity of landslide processes while ensuring objective prioritization of key contributing factors (Yalcin, 2008; Shahabi & Hashim, 2015).

Data Sources and Thematic Layer Preparation

Ten landslide-conditioning factors were selected based on geomorphic significance, past literature, and local field characteristics: elevation, slope, drainage density, distance to lineament, distance to road, topographic wetness index (TWI), rainfall, earthquake density, Normalized Difference Vegetation Index

(NDVI), and land use/land cover (LULC). All datasets were projected to UTM Zone 45N and resampled to 30 m spatial resolution to ensure uniformity.

The SRTM DEM (30 m) served as the base dataset for deriving elevation, slope, and TWI using hydrological and surface analysis tools in ArcGIS. Drainage networks were digitized from SOI toposheets and Sentinel-2 imagery, and drainage density was generated via line density computation. Structural lineaments were interpreted from Sentinel-2 imagery and GSI geological maps; Euclidean distance was computed to represent distance to lineaments. Similarly, distance to road was calculated from digitized transportation layers. Rainfall data (2015–2025) from TRMM and PERSIANN-CCS were processed using the Inverse Distance Weighting (IDW) method to obtain mean annual precipitation. Earthquake epicentres were mapped from GSI seismic archives and converted to an earthquake density raster using point density estimation. NDVI was derived from near-infrared and red bands of Sentinel-2 imagery, and LULC was generated through supervised classification using the maximum likelihood algorithm. All selected factors are strongly associated with the triggering or conditioning of slope failures, either by influencing terrain stability (e.g., slope, elevation, rock structure) or hydrological behaviour (e.g., rainfall, TWI), or by modifying slope resistance through vegetation and anthropogenic alterations (Pourghasemi et al., 2012).

Reclassification and Standardization of Factors

To bring all datasets to a common comparison platform, each factor was reclassified into four susceptibility classes—very high, high, moderate, and low—based on intrinsic parameter thresholds, geomorphological interpretation, and previously established criteria from similar mountainous catchments (Akgun & Türk, 2011; Saha et al., 2023). The reclassification converted continuous raster values into discrete susceptibility classes. Higher ranks were assigned to conditions that encourage slope instability, such as steep slopes, high precipitation, shorter distance to lineaments and roads, high drainage density, low NDVI (barren/grassland), and earthquake-dense zones.

This standardization step ensured that all thematic layers contributed comparably to the multi-criteria modelling procedure without bias from differences in numerical scale.

Analytical Hierarchy Process (AHP) Weighting

The **Analytical Hierarchy Process (AHP)** is a multi-criteria decision-making technique introduced by **Saaty (1980)** to derive numerical weights representing the relative importance of multiple factors in a structured and rational manner. AHP converts expert judgment into a pairwise comparison matrix, allowing subjective preferences to be transformed into quantitative mathematically verified weights.

In AHP, each conditioning factor is compared with every other factor on **Saaty’s 1–9 scale**, where 1 indicates equal importance and 9 represents extreme dominance of one factor over another. These comparisons generate a **pairwise comparison matrix**.

Each column is normalized by its column sum, and the geometric mean of each row produces the preliminary weights (W_i). The weights are finalized after consistency validation, which ensures that judgments are not random or contradictory.

AHP calculates the **Consistency Index (CI)** as:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

Where:

- $\lambda_{\max}$ = maximum eigenvalue of matrix
- n = number of parameters

Then the **Consistency Ratio (CR)** is computed as:

$$CR = \frac{CI}{RI}$$

Where **RI** is the *Random Index* proposed by Saaty (1980). If **CR** < **0.1**, the comparison matrix is acceptably consistent; if **CR** > **0.1**, the matrix should be revised.

Due to the multi-dimensional nature of landslide processes, relative weighting of conditioning factors is essential for accurate susceptibility modelling. The Analytical Hierarchy Process (AHP) (Saaty, 1980) was used to quantify the relative importance of the ten parameters. A pairwise comparison matrix was developed according to Saaty's 1–9 preference scale, informed by their role in slope failure reported in local studies and global literature. The matrix was normalized, and factor weights were calculated using the geometric mean method.

To verify judgment consistency, a Consistency Ratio (CR) was computed using the principal eigenvalue of the matrix. The CR value of 0.085, below the accepted threshold of 0.1 (Saaty, 1990), confirms that factor comparisons were logically consistent, and the assigned weights were reliable for further modelling.

Weighted Overlay Analysis for Susceptibility Mapping

The final susceptibility map was generated by integrating all reclassified and weighted factors in ArcGIS using the Weighted Overlay Analysis (WOA) tool. Each thematic raster was multiplied by its AHP-derived weight, and the products were summed to compute the Landslide Susceptibility Index (LSI):

$$LSI = \sum_{i=1}^n (W_i \times R_i)$$

where LSI is the Landslide Susceptibility Index, W_i is the normalized weight of the i^{th} factor, and R_i is the reclassified rank assigned to each class. This approach ensures that factors with greater influence exert stronger control on the susceptibility output. The final composite LSI map was classified into four categories such as, Low, Moderate, High, and Very High susceptibility zones using the natural breaks algorithm.

This methodological framework effectively captures the interplay of terrain, hydro-meteorological conditions, geological structures, vegetation cover, and anthropogenic activity, offering a scientifically robust representation of landslide susceptibility across Patan Taluka. The methodological workflow is illustrated in **Figure 2**.

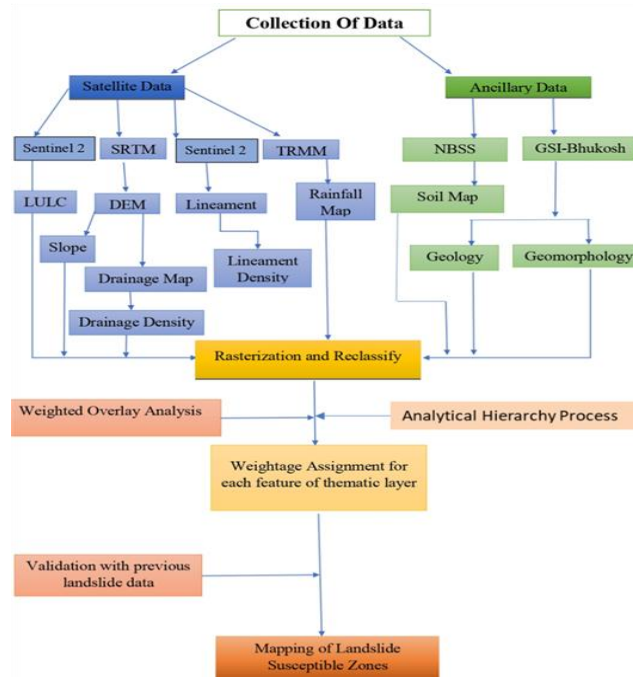


Figure 2: Methodology chart

Results and Discussion

The integration of AHP-derived weights with Weighted Overlay Analysis produced a detailed Landslide Susceptibility Map (LSM) for Patan Taluka, highlighting spatial variations in slope instability across the landscape. The results reflect the combined influence of topography, hydrology, rock structure, seismicity, vegetation cover, and human interventions that characterize the Western Ghats. The final map delineates areas most vulnerable to landslides by synthesizing ten conditioning factors, thereby offering a spatially explicit representation of slope failure potential.

Influence of Landslide Conditioning Factors

Among the ten parameters considered, **slope, rainfall, distance to lineament, drainage density, and LULC/NDVI** emerged as the most influential in the AHP weighting process, underscoring their dominant role in slope destabilization.

Slope was the highest contributing factor to landslide occurrence. Steep slopes ($>35^\circ$), particularly in the western and north-western escarpment region, were associated with the highest susceptibility due to gravitational stress, intense runoff, and the presence of laterite–basalt contacts that weaken under heavy precipitation. Conversely, gentler slopes in the central and eastern portions of the taluka were linked to lower susceptibility, consistent with agricultural and settlement-dominated areas where terrain gradients are more subdued.

Rainfall was identified as the principal triggering agent. Orographic intensification along the Western Ghats results in annual precipitation exceeding 3500–4000 mm in the western highlands, greatly increasing pore-water pressure, soil saturation, and basal shear stress. The spatial overlap of heavy rainfall zones with Very High susceptibility regions supports the role of monsoon rainfall in triggering slope failures.

Distance to lineament strongly influenced susceptibility because lineaments represent fractures, faults, or shear planes within Deccan Basalts. Areas situated closer to structural discontinuities exhibited higher susceptibility, indicating that terrain underlain by fractured lithology or tectonically weakened rocks is more prone to failure. This observation aligns with previous studies demonstrating the role of structurally controlled discontinuities in landslide initiation in volcanic and escarpment terrains.

Drainage density contributed significantly to instability by accelerating surface runoff, gully erosion, and toe cutting. Regions with dense drainage networks—particularly along the Koyana and Morna valleys—display high susceptibility, suggesting that fluvial incision enhances slope sensitivity.

LULC and NDVI modulated susceptibility by influencing vegetation cover and soil protection. Western forested sectors exhibited low susceptibility due to dense root reinforcement and reduced soil erosion, whereas barren land, exposed lateritic terrain, agricultural fields, and road cuts demonstrated higher vulnerability. **Distance to road** also played a critical role locally, indicating the destabilizing effect of slope excavation and embankment failures along transportation corridors.

TWI, elevation, and earthquake density contributed to susceptibility with secondary but meaningful influence. High TWI zones highlight areas prone to water accumulation, while higher elevations coincided with landslide-prone escarpments. Areas influenced by seismic tremors around the Koyna reservoir corresponded to moderate-to-high susceptibility classes, confirming the role of seismic perturbation in rock weakening and slope destabilization.

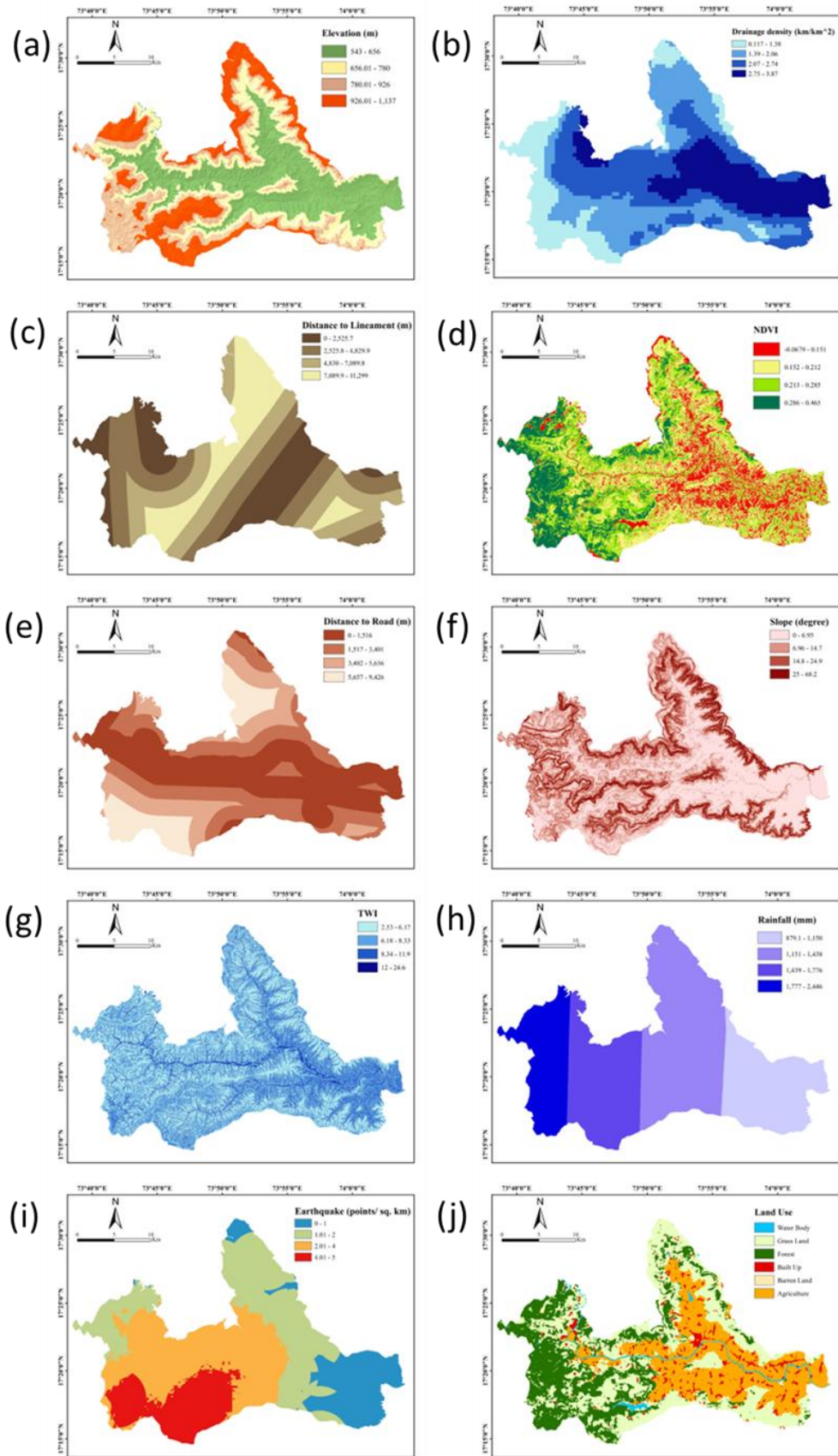


Figure 3: Causative factors used for landslide susceptibility mapping namely: (a) Elevation, (b) Drainage Density, (c) Distance to lineament, (d) Normalized Difference Vegetation Index(NDVI), (e) Distance to road, (f) Slope, (g) Topographic Wetness Index(TWI), (h) Rainfall, (i) Earthquake density, (j) Land use/land cover(LULC)

Spatial Distribution of Susceptibility Zones

The final Landslide Susceptibility Index (LSI) was classified into four categories: Very High, High, Moderate, and Low. The spatial trends reveal clear geomorphological control over susceptibility distribution:

- Very High Susceptibility (~18%) - Concentrated along the western escarpment, including Mirgaon, Koyananagar, Ambeghar, Rasati, Miraswadi, and landslide-prone segments of the Karad–Chiplun road corridor. These regions exhibit steep gradients, high rainfall, fractured basalt, and anthropogenic slope modification.
- High Susceptibility (~16%) - Found adjacent to Very High zones, particularly around Mulgaon, Kusrud, Dhokawale, and upper catchment localities. These areas exhibit moderate–steep slopes subject to combined structural and hydrological influences.
- Moderate Susceptibility (~48%) - Dominant across central and eastern Patan, reflecting agricultural lands, plantation zones, and moderate-gradient slopes. Although comparatively stable, prolonged rainfall or unregulated land-use conversion may activate failures.
- Low Susceptibility (~18%) - Restricted to low-relief valley floors, plateau surfaces, and densely forested western belts. These areas are geomorphologically stable with minimal evidence of past slope failures.

Table 1: *Classes and ranking of the parameters*

Sr. No.	Parameters	Classes	Ranking	Weightages
1	Elevation (m)	1137-925.02	1	17
		925.02-778.27	2	
		778.27-654.811	3	
		654.811-543	4	
2	Drainage Density (km/sq. km)	2.75 - 3.87	1	13
		2.07 - 2.74	2	
		1.39 - 2.06	3	
		0.117 - 1.38	4	
3	Distance to Lineament (m)	0 - 2,525.7	1	06
		2,525.8 - 4,829.9	2	
		4,830 - 7,089.8	3	
		7,089.9 - 11,299	4	
4	NDVI	0.286 - 0.465	1	11
		0.213 - 0.285	2	
		0.152 - 0.212	3	
		-0.0679 - 0.151	4	
5	Distance to Road (m)	0 - 1,516	1	04
		1,517 - 3,401	2	
		3,402 - 5,656	3	
		5,657 - 9,426	4	
6	Slope (Degree)	25 - 68.2	1	14
		14.8 - 24.9	2	
		6.96 - 14.7	3	

		0 - 6.95	4	
7	TWI	12 - 24.6	1	08
		8.34 - 11.9	2	
		6.18 - 8.33	3	
		2.53 - 6.17	4	
8	Rainfall (mm)	1,777 - 2,446	1	10
		1,439 - 1,776	2	
		1,151 - 1,438	3	
		879.1 - 1,150	4	
9	Earthquake Density (Points/sq.km)	4.01 - 5	1	06
		2.01 - 4	2	
		1.01 - 2	3	
		0 - 1	4	
10	LULC	Built Up	1	11
		Agriculture & Forest Land	2	
		Grass & Barren Land	3	
		Waterbody	4	
		Total	100	

Table 2: Pairwise comparison matrix for ten influencing layers developed for landslide susceptibility mapping using AHP

Parameter	Elevation	Drainage Density	Distance to Lineament	NDVI	Distance to Road	Slope	TWI	Rainfall	Earthquake Density	LULC	Influence (%)
Elevation	1	3.00	6.00	5.00	6.00	3.00	4.00	5.00	7.00	6.00	28.8
Drainage Density	0.33	1	6.00	4.00	4.00	0.50	5.00	5.00	7.00	5.0	17.9
Distance to Lineament	0.17	0.17	1	0.25	0.20	0.17	0.33	0.20	3.00	0.25	2.3
NDVI	0.20	0.25	4.00	1	4.00	0.25	3.00	3.00	5.00	3.00	9.8
Distance to Road	0.17	0.25	5.00	0.25	1	0.25	0.50	0.33	4.00	2.00	4.7
Slope	0.33	2.00	6.00	4.00	4.00	1	4.00	4.00	7.00	4.00	19
TWI	0.25	0.20	3.00	0.33	2.00	0.25	1	0.50	4.00	1.00	4.9
Rainfall	0.20	0.20	5.00	0.33	3.00	0.25	2.00	1	4.00	2.00	6.7
Earthquake Density	0.14	0.14	0.33	0.20	0.25	0.14	0.25	0.25	1	0.25	1.7
LULC	0.17	0.20	4.00	0.33	0.50	0.25	1.00	0.50	4.00	1	4.2
Consistency Index											0.127
Random Index											1.49
Consistency Ratio											0.085

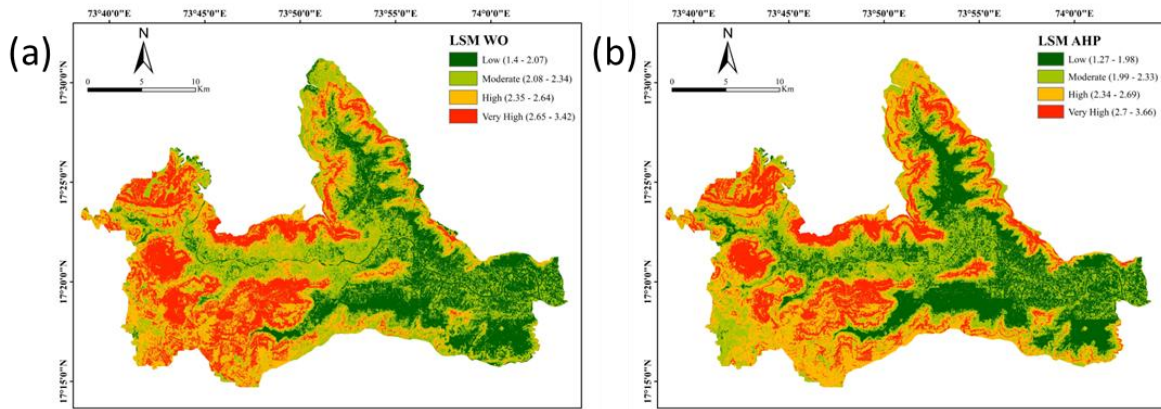


Figure 4: Landslide susceptibility map using: (a) Weighted Overlay (WO) Analysis, (b) Analytical Hierarchy Process (AHP)

Field Validation and Comparison with Observed Landslide Events

Field verification and comparison with historical records revealed strong concordance between modelled susceptibility and actual landslide sites. Villages repeatedly affected by past landslides—including Mirgaon, Miraswadi, Koyananagar, Ambeghar, and segments of the Karad–Chiplun highway—fall predominantly within the Very High and High susceptibility classes. This agreement validates the reliability of the AHP–WOA model and confirms that the selected conditioning factors effectively capture real-world slope failure controls.

Interpretation in the Context of Western Ghats Geomorphology

The susceptibility pattern reflects the broader geomorphic organisation of the Western Ghats: a steep escarpment zone with high rainfall, deep dissection, multi-tiered basalt flows, and tectonic discontinuities. The interface of intensified monsoon rainfall, steep terrain, and fractured basalts acts as the fundamental driver of slope instability, while road cutting, agricultural expansion, and settlement encroachment amplify risk in already fragile terrain. This emphasizes the need for regulated land-use planning, controlled slope excavation, and interception of runoff in vulnerable hill-slope environments.

Overall, the results demonstrate that landslide susceptibility in Patan Taluka is governed by a combination of intrinsic terrain properties and external triggering mechanisms. The generated LSM provides essential spatial guidance for disaster risk mitigation, infrastructure planning, and community safety decision-making in the Western Ghats.

Conclusion

This study provides a comprehensive evaluation of landslide susceptibility in Patan Taluka, Satara District, situated within the geomorphically fragile Western Ghats of Maharashtra. By integrating remote sensing datasets, field observations, and multi-criteria decision-making techniques in a GIS environment, a reliable Landslide Susceptibility Map (LSM) was developed using the Analytical Hierarchy Process (AHP) and Weighted Overlay Analysis (WOA). The adopted framework successfully incorporates the spatial variability of ten major conditioning factors—elevation, slope, drainage density, distance to lineament, distance to road, topographic wetness index (TWI), rainfall, earthquake density, NDVI, and land use/land cover (LULC)—which collectively regulate slope stability in the region.

The results indicate that approximately 34% of the study area falls under High to Very High susceptibility, concentrated mainly along the western escarpment and structurally weakened zones where steep slopes, intense monsoonal precipitation, fractured basalt, and anthropogenic slope modifications converge. Villages including Mirgaon, Koyananagar, Ambeghar, Rasati, Dhokawale, and Miraswadi, along with sections of the Karad–Chiplun highway, are identified as landslide hotspots requiring priority attention. Moderate susceptibility (48%) characterizes much of the mid-slope terrain where slope gradients are lower but long-duration rainfall or developmental activities may trigger

failures. Only 18% of the area falls within the Low susceptibility class, mostly in stabilized forested and gently sloping landscapes.

The high predictive performance of the AHP–WOA model is supported by the low Consistency Ratio (CR = 0.056) and by strong agreement between susceptibility outputs and documented landslide occurrences. This confirms that the combination of expert-driven factor weighting and geospatial overlay modelling is well suited to capture both intrinsic terrain conditions and external triggering mechanisms in the Western Ghats.

The findings of this study hold considerable value for regional planning, slope-specific engineering design, climate-resilient infrastructure placement, and risk-sensitive land-use regulation. The susceptibility map provides a scientific basis for hazard mitigation, micro-zonation of vulnerable settlements, and formulation of early warning protocols. Future research may enhance the approach by incorporating machine learning and deep learning-based models, InSAR-derived ground deformation measurements, UAV-based terrain monitoring, and geotechnical validation to further improve spatiotemporal prediction and early detection of landslide-prone slopes.

References

- Akgun, A., & Türk, N. (2011). Landslide susceptibility mapping using AHP and GIS techniques: A case study in Turkey. *Environmental Earth Sciences*, 66, 2061–2075.
- Cruden, D. M., & Varnes, D. J. (1992). Landslide types and processes. In *Landslides: Investigation and Mitigation* (pp. 36–75). Transportation Research Board Special Report 247.
- Eastman, J. R. (2006). *IDRISI Andes Tutorial*. Clark Labs, Massachusetts.
- Froude, M. J., & Petley, D. N. (2018). Global fatal landslide occurrence from 2004 to 2016. *Natural Hazards and Earth System Sciences*, 18(8), 2161–2181.
- Geological Survey of India (GSI). (2009). *Landslide Hazard Zonation Atlas of India*. Geological Survey of India.
- Malczewski, J. (1999). *GIS and Multi-Criteria Decision Analysis*. John Wiley & Sons.
- Pourghasemi, H. R., Pradhan, B., Gokceoglu, C., & Dey, N. (2012). A comparative study using AHP and fuzzy AHP models for landslide susceptibility mapping. *International Journal of Digital Earth*, 5(6), 540–573.
- Saaty, T. L. (1980). *The Analytic Hierarchy Process*. McGraw-Hill.
- Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research*, 48(1), 9–26.
- Saha, S., Mondal, S., Tripathi, N., & Martha, T. R. (2023). Recent landslides in the Western Ghats: geomorphology, triggers, and implications. *Geomorphology*, 432, 108761.
- Shahabi, H., & Hashim, M. (2015). Landslide susceptibility mapping using GIS-based statistical models. *Environmental Earth Sciences*, 73, 1–14.
- Thigale, S. S., & Khandge, A. M. (1996). Seismotectonics around Koyna–Warna region and its implications. *Current Science*, 70(7), 619–622.
- Yalcin, A. (2008). GIS-based landslide susceptibility mapping using AHP. *Environmental Geology*, 57, 791–803.



Groundwater Monitoring- Data Management, Assessment and its Uncertainties Statistical Assessment of Underground Water Quality at Moradabad (Uttar Pradesh, India)

G. K. Rastogi, N. Kumar and D. K. Sinha

Department of Chemistry, K.G.K.(P.G.) College, Moradabad

E-mail: gaurav_22677@rediffmail.com , navk009@yahoo.com, dkskgk@rediffmail.com

Abstract

Water quality indices for underground water at six different sites at Moradabad have been calculated with the help of water quality standards prescribed by W.H.O. and values of water quality physico-chemical parameters estimated for all the sites following standard methods and procedures of sampling and estimation as well. The underground water invariably at all the sites of study was found to be severely contaminated and unfit for human consumption and other domestic usage. Some strict and effective measures are urgently needed for underground water quality management in the catchment area of study. Present study is indicative of men's disregard towards nature.

Keywords: Underground water quality, water quality index, unit weight, quality rating

Introduction

Water is absolutely essential for healthy living. It plays an indispensable role in the life of every species that survive in this world and is required by all living organisms for their existence. Today, human activities are constantly adding industrial, domestic and agricultural wastes to ground water reservoirs at an alarming rate. Ground water contamination is generally irreversible i.e. once it is contaminated; it is difficult to restore the original quality of aquifer (Mahapatra 2005, Khan 2005)

Water quality index (WQI) is regarded as one of the most effective way to communicate water quality. The data obtained through quantitative analysis and W.H.O water quality standards are used for calculating water quality indices (Sinha 1994, Pradhan 2001, Sinha 2006, Rajmohan 2003, W.H.O. 1971). The objective of calculating WQI and comparing it with the standard assumption is to assess underground drinking water quality at Moradabad.

Moradabad is a 'B' class city of western Uttar Pradesh having urban population more than 38 lakhs. Moradabad is situated at the bank of Ram Ganga river and its altitude from the sea level is about 670 feet. It is extended from Himalaya in north to Chambal river in south. It is at 28°20', 29°15' N and 78°4', 79°E. District Bijnor and Nainital are in the north, Rampur in the east, Ganga river in the west and district Budaun is in the north of district Moradabad. Moradabad has seen rapid industrialization and population growth during the last few decades. The major industries are brassware, steelware, paper mills, sugar mills, crushers, dye factories and a number of associated ancillaries. Most of these industries and different kinds of human activities are playing their roles in multiplying the level of underground drinking water pollution.

Material and methodology

Six different sites at Moradabad were selected in order to study the physico-chemical characteristics of underground drinking water of India Mark II (IM2) hand pumps. The samples were collected during 2007 following the standard methods of sampling. The standard methods and procedures were used for quantitative estimation of water quality parameters (APHA 1995, Merck 1974). All the chemicals of anal R grade were used for this purpose. The standards prescribed by W.H.O. were used for calculation of water quality indices. Estimated water quality physico-chemical parameters are – pH value, conductivity, turbidity, dissolved oxygen, biological oxygen demand, chemical oxygen demand, total

hardness, calcium, magnesium, chloride, total solids, total dissolved solids, iron, alkalinity, fluoride, sulphate and free CO₂. Details of sampling sites are given in Table 1.:

Table 20 : Details of sampling locations

Sl. No.	No. and Name of site	Location of site	Type of hand pump	Depth of boaring	Type of source	Apparent water quality
1.	I, Bus Station	1 km north to Tehsil	India Mark II	Approx. 33 meters	Only source	Water becomes turbid on standing
2.	II, Railway Station	200 m. west to site no. I	India Mark II	Approx. 30 meters	Only source	Neat and clear water
3.	III, Town Hall	200 m. west to site no. IV	India Mark II	Approx. 33 meters	Only source	Water colour turns yellowish on standing
4.	IV, Sadar Tehsil	Tehsil head quarter	India Mark II	Approx. 30 meters	Only source	Neat and clear water
5.	V, District Eye Hospital	1 km west to site no. IV	India Mark II	Approx. 33 meters	Only source	Water colour turns yellowish on standing
6.	VI, District Hospital	100 m. west to site no. V	India Mark II	Approx. 30 meters	Only source	Water becomes turbid on standing

WQI of underground drinking water collected at six different sites has been calculated using the methods proposed by Horton and modified by Tiwari and Mishra (Horton 1965, Tiwari 1985, Tiwari 1986). According to the role of various parameters on the basis of importance and incidence on the overall quality of drinking water, the rating scales were fixed in terms of ideal values of different physico-chemical parameters. Even if, they are present, they might not be the ruling factor. Hence, they were assigned zero values. For calculating WQI, following four equations were used

- Quality rating, $Q_n = 100 [(V_n - V_i) / (V_s - V_i)]$
 here,
 V_n = actual amount of nth parameter
 V_i = the ideal value of this parameter
 $V_i = 0$, except for pH and D.O.
 $V_i = 7.0$ for pH; $V_i = 14.6$ mg/lit for D.O.
 V_s = recommended W.H.O. standard of corresponding parameter

- Unit weight (W_n) for various parameters is inversely proportional to the recommended standard (S_n) for the corresponding parameter.

$$W_n = K / S_n$$

- here, S_n = world-widely accepted drinking water quality standard prescribed by W.H.O.

K = constant

$$n=18$$

$$\sum_{n=1} W_n = 1, \text{ considered here}$$

$$n=1$$

- Sub indices, $(SI)_n = (Q_n)^{W_n}$

- The overall WQI is calculated by taking geometric mean of these sub-indices.

$$WQI = \prod_{n=1}^{n=18} (SI)_n = \prod_{n=1}^{n=18} (Q_n)^{W_n}$$

OR

$$WQI = \text{antilog}_{10} \left[\sum_{n=1}^{n=18} W_n \log_{10} Q_n \right]$$

To include, the collective role of various physico-chemical parameters on the overall quality of drinking water, quality status is assigned on the basis of calculated values of water quality indices. On the basis of a number of water pollution studies, the following assumptions were made with reference to assess the extent of pollution or quality of drinking water. The assumptions were: WQI < 50: fit for human consumption; WQI < 80: moderately polluted; WQI > 80: excessively polluted; WQI > 100: severely polluted.

Results and discussion

The physico-chemical parameters with their W.H.O. Standards and unit weights (W_n) assigned with the help of equation no. 2 are listed in Table 2. Site-wise and parameter-wise estimated values (V_n) and calculated quality rating (Q_n) are presented in Table 3. Site-wise calculated values of WQI are given in Table 4. Site-wise variation of WQI is depicted in Figure 1.

Table 2: Parameter-wise W.H.O. standards and their assigned unit weights

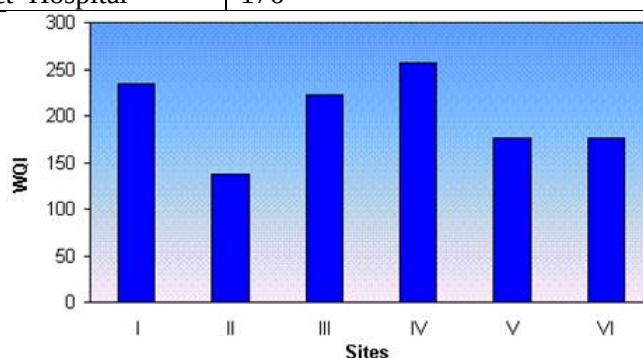
Sl. No.	Parameter	W.H.O. Standard	Assigned Unit Weight (W_n)
1	pH value	7 - 8.5 (8.0)	0.016669
2	Conductivity ($\mu\text{S}/\text{cm}$)	0.300	0.444503
3	Turbidity (NTU)	5.0	0.026670
4	Dissolved Oxygen (ppm)	5.0	0.026670
5	Biological Oxygen Demand (ppm)	6.0	0.022225
6	Chemical Oxygen Demand (ppm)	10.0	0.013335
7	Total Hardness (ppm)	100	0.001334
8	Calcium (ppm)	100	0.001334
9	Magnesium (ppm)	30	0.004446
10	Chloride (ppm)	200	0.000667
11	Total Solids (ppm)	500	0.000267
12	Total Dissolved Solids (ppm)	500	0.000267
13	Iron (ppm)	0.5	0.266702
14	Alkalinity (ppm)	100	0.001334
15	Flouride (ppm)	1.0	0.133351
16	Sulphate (ppm)	500	0.000267
17	Zinc (ppm)	5.0	0.026670
18	Free CO_2 (ppm)	10.0	0.013335

Table 3: Parameter- wise and site-wise estimated actual value (Vn) and calculated quality rating (Qn)

Sl. No.	Parameter	Site No. I		Site No. II		Site No. III		Site No. IV		Site No. V		Site No. VI	
		Vn	Qn	Vn	Qn	Vn	Qn	Vn	Qn	Vn	Qn	Vn	Qn
1	pH value	7.26	26	7.40	40	7.48	48	7.51	51	7.47	47	7.32	32
2	Conductivity ($\mu\text{S}/\text{cm}$)	1.14	380	1.0	333.33	1.16	386.67	1.10	366.67	1.14	380	1.14	380
3	Turbidity (NTU)	20	400	2	40	12	240	2	40	12	240	10	200
4	Dissolved Oxygen (ppm)	2.40	127.08	2.20	129.17	2.8	122.92	2.40	127.08	2.60	125	2.30	128.13
5	Biological Oxygen Demand (ppm)	10	166.67	12	200	16	266.67	14	233.38	14	233.38	14	233.38
6	Chemical Oxygen Demand (ppm)	60	600	80	800	58	580	58	580	50	500	60	600
7	Total Hardness (ppm)	320	320	304	304	300	300	340	340	352	352	328	328
8	Calcium (ppm)	89.6	89.6	75.20	75.20	51.20	51.20	54.40	54.40	70.40	70.40	84.8	84.8
9	Magnesium (ppm)	23.34	77.80	28.2	94	41.81	139.37	49.59	165.30	42.79	142.63	28.2	94
10	Chloride (ppm)	52	26	56	28	64	32	68	34	58	29	52	26
11	Total Solids (ppm)	400	80	350	70	450	90	380	76	390	78	420	84
12	Total Dissolved Solids (ppm)	380	76	320	64	435	87	330	66	360	72	380	76
13	Iron (ppm)	1.2	240	0.28	56	1.10	220	0.28	56	0.58	116	0.51	102
14	Alkalinity (ppm)	388	388	384	384	396	396	288	288	388	388	398	398
15	Flouride (ppm)	1.07	107	1.05	105	1.07	107	0.80	80	0.64	64	0.78	78
16	Sulphate (ppm)	80	16	80	16	80	16	80	16	110	22	80	16
17	Zinc (ppm)	0.40	8	0.20	4	0.10	2	0.10	2	0.20	4	0.40	8
18	Free CO_2 (ppm)	40	400	32	320	38	380	34	340	32	320	36	360

Table 4: Site-wise calculated values of Water Quality Index at Moradabad

Sl. No.	No. and Name of site	Water Quality Index
1	I, Bus Station	234
2	II, Railway Station	137
3	III, Town Hall	222
4	IV, Sadar Tehsil	257
5	V, District. Eye Hospital	176
6	VI, District Hospital	176

**Fig. 1: Site-wise variation of Water Quality Index at Moradabad**

Critical analysis of the data of the WQI presented in Table 4. and its comparison with standard assumptions revealed following facts regarding the level of drinking water pollution at Moradabad during the course of study.

The observed range of water quality index is 137-257. The underground drinking water of IM2 hand pumps at Moradabad are severely contaminated with WQI values more than 100 invariably at all the sites of study and is unfit for consumption and other domestic purposes. The present study is an approach to assess drinking water quality statistically. The results of estimated values of different physico-chemical parameters and calculated values of WQI for assessment of water quality.

Conclusion

On the basis of above discussion, it may be concluded that the underground drinking water is severely polluted in the catchment area of study at Moradabad. The drinking water is polluted with reference to almost all the water quality physico-chemical parameters studied. The water is unfit for human consumption and other domestic usage. People dependent on this water are prone to health hazards of contaminated drinking water. Some strict and effective measures are urgently needed for underground water quality management in the catchment area of study. Water quality index is proved to be an effective tool for drinking water quality assessment.

References

- Mahaptra , M.K. and Mishra , H.S. , Ground water pollution in Subarampur and Nuapada district of Orissa , Poll.Res. , 24(4) , 863-865 (2005).
- Khan , N. , Mathur , A. and Mathur , R. , A study on drinking water quality in Lashkar(Gwalior) , Indian J. Env. Prot. , 25(3) , 222-224(2005).
- Sinha , D.K. and Srivastava , A.K. , Water quality index of river Sai at Rae Bareli for pre-monsoon period and after the onset of monsoon , Indian J. Env. Prot. , 14(5) , 340-345 (1994).
- Pradhan , S.K. , Patnaik , D. and Rout , S.P. , Ground water quality index for ground water around a phosphatic fertilizer plant , Indian J. Env. Prot. , 21(4) , 355-358 (2001).
- Sinha , D.K. and Saxena , R. , Statistical assessment of underground drinking water contamination and effect of monsoon at Hasanpur , J.P. Nagar (Uttar Pradesh , India) , Journal of Environ. Science & Engg. , 48(3) , 157-164 (2006) .
- Rajmohan , N. et al. , Major correlation in ground water of Kancheepuram region , South India , Indian J. Environ. Hlth , 45(1) , 1-5 (2003).
- W.H.O. , International Standards for Drinking Water , World Health Organization , Geneva (1971) .
- APHA , AWWA , WPCF , Standard Methods for Examination of Water and Wastewater , Washington , D.C. 2005 , U.S.A. 19th ed. (1995) .
- Merck , E. , Testing of Water , Darmstadt , Federal Republic of Germany (1974) .
- Horton , R.K. , A index number system for rating water quality , J. Water Poll , Cont. Fed. , 37 , 300 (1965) .
- Tiwari , T.N. and Mishra , M. , A preliminary assignment of water quality index of major Indian rivers , Indian J. Env. Prot. 5(4) , 276-279 (1985) .
- Tiwari , T. N. , Das , S.C. and Bose , P.K. , Weighed geometric water quality index for river Jhelum in Kashmir , Journal M.A.C.T. , 19 , 33-41 (1986).



Delineating Groundwater Potential Zones in Dibrugarh District, Assam, India using GIS and Analytical Hierarchy Process (AHP)

Bijoy K. Chetia, Jayashri Dutta, William Narzary

Jal Jeevan Mission, Assam, India
E-mail: bijoykrishnaster@gmail.com

Abstract

Integrating Remote Sensing and Geographic Information System (GIS) greatly enhanced the possibilities for groundwater assessment, monitoring and conservation. This study uses GIS and Remote Sensing strategies to accurately identify the Groundwater Potential Zones in Dibrugarh district, Assam, India, facilitating effective groundwater management. The thematic layers viz., geology, geomorphology, drainage density, landuse landcover, slope, lineament density, soil, aquifer depth were used to delineate the Groundwater Potential Zone (GPWZ). Analytical Hierarchy Process (AHP) was used to quantify weights and ranks. The assigned weights for the layers geology, geomorphology, drainage density, landuse landcover, slope, lineament density, soil and aquifer depth were 7%, 24%, 9%, 5%, 29%, 5%, 3% and 18% respectively. The groundwater potential zones were categorized as very poor, poor, intermediate, high and very high. The highest area is covered by high groundwater potential zone (3038.02 sq.km) followed by intermediate (267.77 sq. km), very poor (29.71 sq. km), poor (6.81 sq. km) and very high (3.59 sq. km). The area covered by very poor prospect of groundwater is concentrated in the Tipam sandstone formation due to its limited porous and pervious condition. Towards the western extremity, the smallest area with very high groundwater potential was found in the Brahmaputra floodplain. The results will be helpful in better development and supervision of groundwater resources.

Keywords: Groundwater potential · Analytical Hierarchy Process · Geographic Information System · Weighted Overlay · Dibrugarh

1. Introduction

Groundwater is the principal available source of fresh water and a vital element of human life as well as other ecosystems. It acts a crucial role in both rural and urban settings (Magesh et al., 2012). With the increasing population, groundwater demand increases, as a result a tremendous pressure is imposed on the groundwater to meet the requirement. A region which experiences increasing population density faces groundwater scarcity due to over-exploitation and increasing impervious surfaces by urbanization (Arulbalaji et al., 2019). Three-fourths of the houses in India do not have the facility of drinkable water at their premises and 0.6 million people have faced extreme water stress due to lack of adequate freshwater resources (NITI Aayog, 2017-18). Therefore, delineation of groundwater potential zone is necessary to conserve the valuable resource. Assessment of groundwater based on a scientific approach is required for the sustainable development of the resource (Agarwal et al., 2013).

There are different methods of groundwater investigations which are practiced traditionally i.e. drilling, geophysical methods, hydrogeological approaches are time consuming, expensive and tedious method (Murmu et al., 2019). The advent of Remote Sensing and GIS play a significant role in preliminary investigation in understanding the processes of groundwater. The advancement of Remote Sensing and Geographic Information System (GIS) plays an important role in understanding the complex groundwater system. GIS is an outstanding tool which can handle large set of spatial data and analyse the dataset visually in a very fast manner (Krishnamurthy et al., 1996, Upadhyay et al., 2023). Previous literatures practice the GIS platform for the determination of groundwater potential zone and

groundwater vulnerable zones using Analytical Hierarchy Process (AHP), Multi-criteria decision analysis, Multi-influencing Factor (MIF), DRASTIC model etc. (Wei et al., 2021, Biswas et al., 2012, Magesh et al., 2012, Krishnamurthy et al., 1996, V et al., 2024). The present study uses the Weighted Overlay method using Analytical Hierarchy Process to delineate the groundwater potential zone with the help of eight thematic layers and calculate the area of each potential zones.

2. Materials and methods

2.1 Study area

Dibrugarh District is located in the northeastern part of Assam, India, and lies on the southern bank of the Brahmaputra River. Geographically, it is situated between latitudes 27°5' N to 27°42' N and longitudes 94°33' E to 95°29' E (fig 1). The district covers an area of approximately 3,381 square kilometres and is bordered by Dhemaji and Lakhimpur districts to the north, Tinsukia district to the east, and Sivasagar district to the west. To the south, Dibrugarh is bounded by the state of Arunachal Pradesh, with the Patkai Hills forming a natural barrier. The region is known for its rich alluvial plains, formed by the deposition of sediments from the Brahmaputra and its tributaries, making it fertile and conducive for tea cultivation, which is a key part of the district's economy. The district experiences a humid subtropical climate, with significant rainfall during the monsoon season.

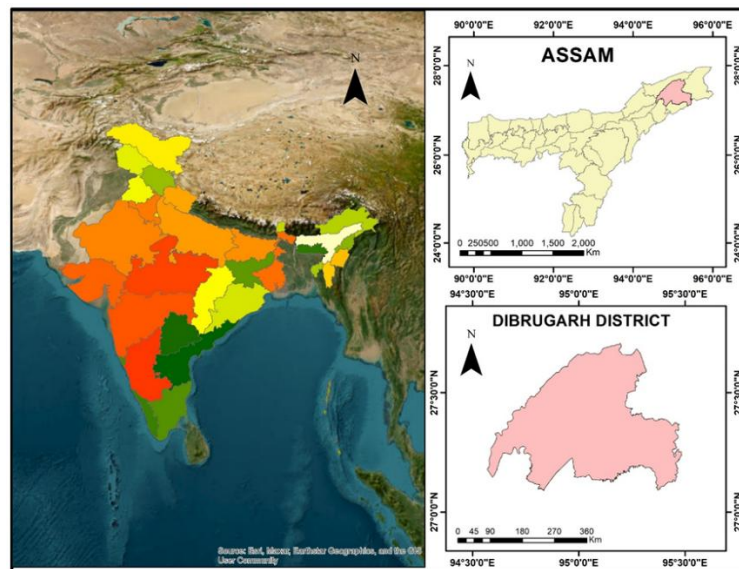


Figure 1: Map showing the study area

2.2 Materials

The methodology adopted for the groundwater potential zone is the weighted overlay using the AHP technique in ArcGIS 10.8.2. Eight criteria were selected viz. geology, geomorphology, lineament density, drainage density, slope, land use land cover, aquifer depth and soil for overlay. Geology and geomorphology maps were taken from the Bhukosh portal of Geological Survey of India (GSI). The lineament density map is prepared from the lineament data of Bhukosh. Drainage density and slope maps are prepared using Alos Palsar DEM data. Landuse landcover (LULC) is prepared from Sentinel 2 imagery processed in Google Earth Engine and soil map was prepared from the Bhuvan NRSC data. Data for aquifer depth were taken from the JJM Assam in-house web application JJM Brain (fig 2).

2.3 Methodology

The layers are converted to raster using ArcGIS 10.8.2. platform and then projected to UTM. The resolution of all rasters transformed into 30m. Weights for all criteria are calculated through Analytical

Hierarchy Process (AHP) using a multi-criterion decision matrix. The Weighted Overlay is done through the ArcGIS Spatial Analyst tool.

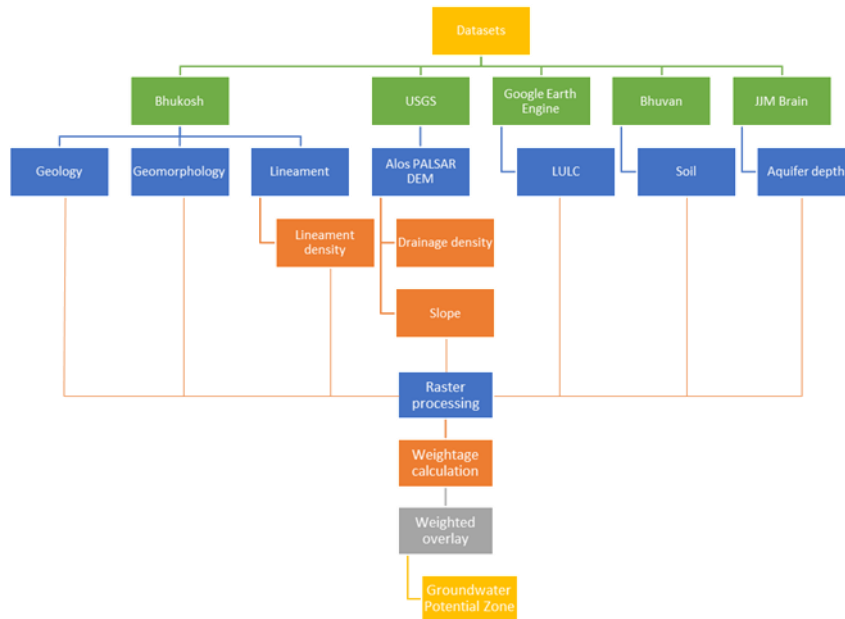


Figure 2: Flowchart of the datasets used for Groundwater Potential Zone mapping

3. Results

3.1 Preparation of thematic maps

Geology

The geology of the area is divided into six categories according to formation viz., Barail formation, Tipam formation, Dihing formation, newer alluvium, older alluvium and undifferentiated quaternary formation. Barail, Dihing and Tipam formations are located in south eastern part of the district where the district shares boundary with Arunachal Pradesh. Newer alluvium is concentrated in the region through which the river Brahmaputra and Dihing are flowing and their floodplain areas. The rest of the area is covered by the older alluvial formation (fig 3).

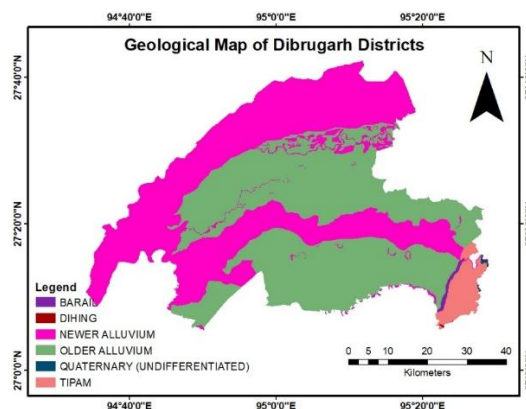


Fig 3: Geological map of the study area

Geomorphology

Geomorphologically, the area is broadly divided into water bodies, alluvial plains, flood plains, hills and valleys, pond, river, dam and reservoir and pediment pediplain complex. Flood plains found in the region is older flood plain, alluvial plain is divided into older alluvial plain and younger alluvial plain, hills and valleys are divided into highly dissected and moderately dissected hills and valleys (fig 4).

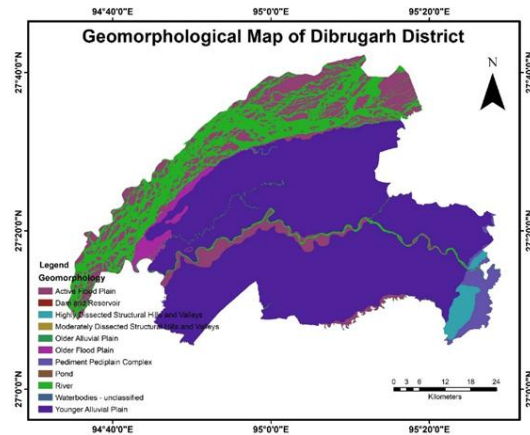


Fig 4: *Geomorphology map of the study area*

Drainage density

Drainage density is the sum of the length of the stream networks per unit area. It is inversely related to the permeability of the aquifer formation. The higher the drainage density, the higher will be the runoff and lower will be the infiltration. The study area is clustered into 5 classes, 0.22 - 1.54 km/km², 1.54 – 2.87 km/km², 2.87 – 4.2 km/km², 4.2 – 5.53 km/km² and 5.53 – 6.86 km/km² (fig 5).

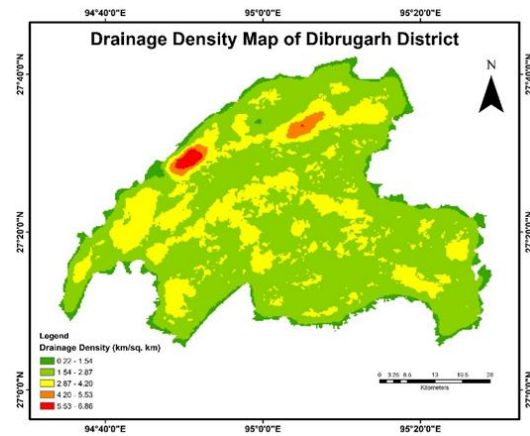


Fig 5: *Drainage density map of the study area*

Landuse landcover

Land use and land cover of the study area are classified into 5 land use classes i.e water body, trees/grassland/flooded vegetation, built-up area, cropland and bare land. Most of the area is covered by trees/grassland/flooded vegetation. Built up area is mainly concentrated in the Dibrugarh city and oil exploration sites of the district in the eastern side (fig 6).

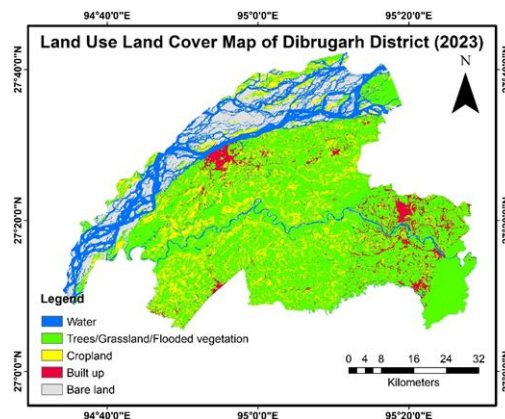
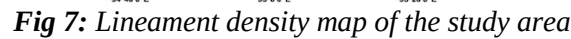
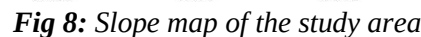


Fig 6: *Landuse landcover (2024) map of the study area*

Lineament is the linear features controlled by geological structures that are the surface expression of the underlying landform. It has significant role in terms of porosity and permeability as it signifies the fold, fault, joints and fracture zones (Margesh et al., 2012). It ranges from 0 to 0.44 km/km² in the area and is classified into 5 classes (fig 7).



Slope is the expression of steepness of an area. The higher percentage of slope upsurges the runoff and reduces the infiltration, thereby increases the erosion. The slope is divided into 2 classes in the study area, $<20\%$ and $>20\%$. With higher steepness in case of $>20\%$, area becomes unsuitable for groundwater potential. Most of the area in the city has gentle slope (fig 8).



Soil is an essential criterion in terms of groundwater potential as it's porosity and permeability control the groundwater percolation. Alluvial soils with good drainage are found in the floodplains of the rivers. Weakly developed soils with limited drainage potential are found in the south-eastern part of the study area (fig 9).



Aquifer depth

Aquifer depth infers the groundwater prospects of an area. Groundwater in Dibrugarh district is found in shallow to medium depth. The aquifer depth in the district ranges from 42.51m to 77.75m and classified into five classes i.e. 42.51m to 53.28m, 53.28m to 59.78m, 59.78m to 63.92m, 63.92m to 66.13m and 66.13m to 77.75m (fig 10).

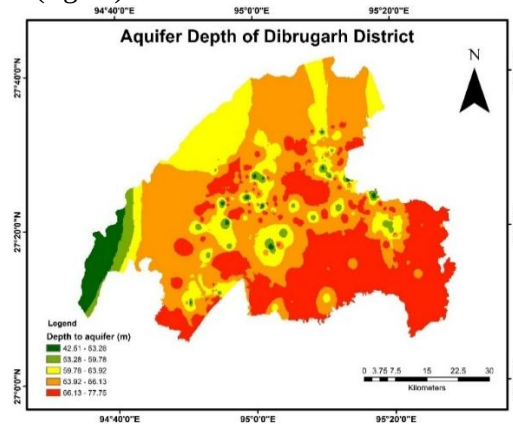


Fig 10: Aquifer depth map of the study area

3.2 Analytical Hierarchy Process for Weightage Calculation

For the calculation of weight, a pairwise comparison matrix should be prepared for decision using the eight criteria according to Saaty's pairwise comparison scale (Saaty, 1980).

Table 1 Scale of pairwise comparison (Saaty, 1980)

Intensity of importance	Definitions
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very strong to extremely strong importance
9	Extreme importance

In the first step, a pairwise comparison matrix is prepared giving the importance by comparing two criteria from the table 1 (table 2). Then, all entries are normalized by summing each column to generate the normalized pairwise comparison matrix. To obtain the normalized weight for each parameter, normalized value of each cell of a respective row is summed up which then divided by the number of criteria (table 3).

Table 2 Pairwise comparison matrix with intensity judgements

	Geology	Geomorphology	Drainage Density	Lineament Density	Slope	Soil	Land use Land cover	Aquifer depth
Geology	1	1/3	1/4	3	1/6	4	1	1/2
Geomorphology	3	1	4	5	1/2	6	9	2
Drainage Density	4	1/4	1	2	1/4	3	2	1/3
Lineament Density	1/3	1/5	1/2	1	1/4	2	1	1/4

Slope	6	2	4	4	1	6	6	2
Soil	1/4	1/6	1/3	1/2	1/6	1	1/4	1/5
Land use Land cover	1	1/9	1/2	1	1/6	4	1	1/8
Aquifer depth	2	1/2	3	4	1/2	5	8	1

Table 3 Normalized pairwise comparison matrix with weights

	Geology	Geomorphology	Drainage Density	Lineament Density	Slope	Soil	Land use land cover	Aquifer depth	Normalized weights
Geology	0.06	0.07	0.02	0.15	0.06	0.13	0.04	0.08	0.07
Geomorphology	0.17	0.22	0.29	0.24	0.17	0.19	0.32	0.31	0.24
Drainage Density	0.23	0.05	0.07	0.10	0.08	0.10	0.07	0.05	0.09
Lineament Density	0.02	0.04	0.04	0.05	0.08	0.06	0.04	0.04	0.05
Slope	0.34	0.44	0.29	0.20	0.33	0.19	0.21	0.31	0.29
Soil	0.01	0.04	0.02	0.02	0.06	0.03	0.01	0.03	0.03
Land use Land cover	0.06	0.02	0.04	0.05	0.06	0.13	0.04	0.02	0.05
Aquifer depth	0.11	0.11	0.22	0.20	0.17	0.16	0.28	0.16	0.18

From the Table 3, it can be interpreted that slope has the highest influence (29%) on the delineation of groundwater potential zone followed by geomorphology (24%), aquifer depth (18%), drainage density (9%), land use land cover (5%), lineament density (5%) and soil (3%). To check the consistency of the judgements, Consistency Index (CI), Consistency Ratio (CR) has been calculated and compared with Random Index (RI). The value of CR should be less than 0.10 to decide the judgement to be consistent. To determine the CI, the principal eigenvalue ($\lambda_{\max}$) and the weighted sum should be calculated (table 5). The weighted sum is determined by multiplying the weight of the criteria in the first row of table 4 with each criteria value in the second row. Eigenvalue, λ is then estimated by multiplying the weighted sum of criteria by its respective weights. The principal eigenvalue, $\lambda_{\max}$ is the average of all eigenvalues.

Table 4 Calculation of weighted sum

	Geology	Geomorphology	Drainage Density	Lineament Density	Slope	Soil	Land use land cover	Aquifer depth	Weighted sum
Normalized weights	0.07	0.24	0.09	0.05	0.29	0.03	0.05	0.18	
Geology	1	0.33	0.25	3	0.17	4	1	0.5	0.61
Geomorphology	3	1	4	5	0.5	6	9	2	2.19
Drainage Density	4	0.25	1	2	0.25	3	2	0.33	0.86
Lineament Density	0.33	0.2	0.5	1	0.25	2	1	0.25	0.39
Slope	6	2	4	4	1	6	6	2	2.6
Soil	0.25	0.17	0.33	0.5	0.17	1	0.25	0.20	0.24
Land use Land cover	1	0.11	0.5	1	0.17	4	1	0.13	0.43
Aquifer depth	2	0.5	3	4	0.5	5	8	1	1.6

Consistency Index, $CI = (\lambda_{\max} - n)/(n-1)$, where n is the number of criteria

Therefore, $CI = (9.76 - 9)/(9 - 1) = 0.09$

Consistency Ratio, $CR = CI / RI$, where $RI = 1.45$ for $n = 9$ (Saaty, 1980)

Therefore, $CR = 0.09 / 9 = 0.07$

Since, CR is less than 0.10, the above decision matrix is consistent (table 5).

Table 5 Calculation of $\lambda_{\max}$, CI and CR

	Weighted sum	Normalized weight	λ	$\lambda_{\max}$	CI	CR
Geology	0.61	0.07	8.28	8.05	0.01	0.005
Geomorphology	2.19	0.24	9.14			
Drainage Density	0.86	0.09	9.10			
Lineament Density	0.39	0.05	8.40			
Slope	2.60	0.29	8.96			
Soil	0.24	0.03	8.60			
Land use Land cover	0.43	0.18	2.42			
Aquifer depth	1.60	0.17	9.48			

Table 6 Scale and influence assigned to the weighted overlay

Parameters	Class	Scale	Weight	Influence (%)
Geology	Barail	5	0.07	7
	Dihing	8		
	Older alluvium	6		
	Newer alluvium	8		
	Quaternary (differentiated)	7		
	Tipam	5		
Geomorphology	Active flood plain	8	0.24	24
	Dam and reservoir	2		
	Highly dissected hills and valleys	6		
	Moderately dissected hills and valleys	5		
	Older alluvial plain	7		
	Older flood plain	7		
	Pediment pediplain complex	3		
	Pond	7		
	River	7		
	Water bodies-unclassified	5		
	Younger alluvial plain	3		
Drainage density	0.22 - 1.54	8	0.09	9
	1.54 - 2.87	7		
	2.87 - 4.20	6		
	4.20 - 5.53	5		
	5.53 - 6.86	4		
Landuse landcover	Water bodies	8	0.05	5
	Trees/grassland/flooded vegetation	8		
	Cropland/shrub and scrub	8		
	Bare land	7		
	Built-up areas	1		

Lineament density	0 - 0.08	3	0.05	5
	0.08 - 0.17	4		
	0.17 - 0.26	5		
	0.26 - 0.35	6		
	0.35 - 0.44	7		
Slope	< 20%	8	0.29	29
	> 20%	1		
Soil	Coarse-loamy, Aehc Fluvaquents & Fine-loamy, Typic Haplaquents	7	0.03	3
	Coarse-loamy, Mollic Fluvaquents & Coarse-silty, Aehc Fluvaquents	8		
	Coarse-loamy, Typic Dystrochrepts & Fine-loamy, Typic Dystrochrepts	6		
	Coarse-silty, Aquic Udifluvents & Fine-loamy, Typic Haplaquents	6		
	Fine, Typic kanhapludalfs & Fine-loamy, Umnhc Dystrochrepts	3		
	Fine-loamy, Typic Dystrochrepts & Clayey, Typic Hapludults	5		
	Fine-loamy, Umbhc Dystrochrepts & Clayey, Typic Hapludults	6		
	Fine-silty, Typic Udifluvents & Typic Psammaquents	8		
	Sandy, Typic Udifluvents & Coarse-loamy, Aquic Udifluvents	7		
Aquifer depth	42.51 - 53.28	8	0.18	18
	53.28 - 59.78	7		
	59.78 - 63.92	6		
	63.92 - 66.13	5		
	66.13 - 77.75	3		

4. Discussion

4.1 Groundwater Potential Zone

Groundwater potential zone map was generated using the ArcGIS Spatial Analyst Weighted Overlay tool from the eight selected criteria assigning the scale and weights from the result of AHP (table 6). The potential zone of the study area is categorized into five groups (i) Very poor, (ii) Poor, (iii) Intermediate, (iv) High and (v) Very high (fig 11). The highest percentage of the area is covered by a high groundwater potential zone encompasses 90.80% area which is followed by intermediate (8%), very poor (0.89%), poor (0.2%) and very high (0.11%). and the lowest percentage of the area is covered by a poor groundwater potential zone i.e. 0.06% (fig 12). The very poor potential zone is concentrated in the Tipam sandstone formation where the porosity and permeability are limited. Intermediate potential zone is concentrated in the built-up area and a part of the Tipam sandstone where infiltration is low due to impervious surface coverings. Near the Brahmaputra River, a small portion of high groundwater potential was found.

4.2 Validation

The generated groundwater potential zone map was validated with the hydro-geomorphological (HGM) map prepared by NRSC (Fig 13). Three points from each zone were selected and overlapped on the HGM map where very low prospects were fall on the region where yield range of well varies from 30 to 50 LPM with depth > 80m and recharge potential is low. The very high potential zone was fall on the region where recharge condition is good with yield potential >800 LPM in less than 30m depth,

whereas high potential zone was fall on the region of yield >800 LPM with the depth range from 30m to 80m. Intermediate potential zone was also fall in the region of yield potential >800LPM where depth range is >80m. On the other hand, low potential zone was fall on the water bodies where the runoff is high.

Since, the selected points of each type of potential zone were perfectly matched with the yield range, depth of the well and recharge condition of the HGM map, it can be inferred that the results of the AHP and weighted overlay have shown a good correlation with the HGM map with a greater accuracy.

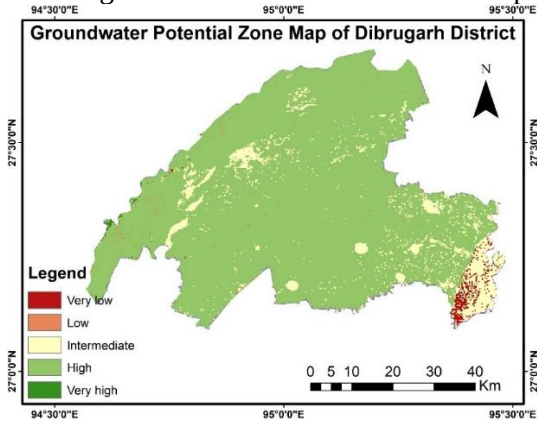


Fig 11: Groundwater Potential Zone map

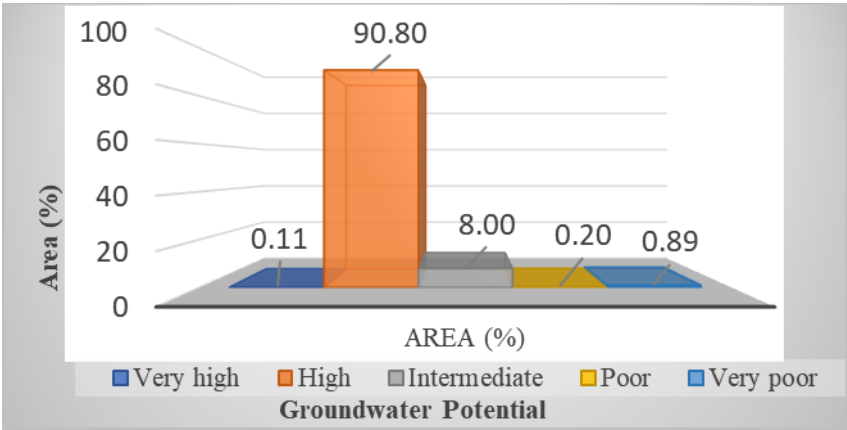


Fig 12: Bar diagram of calculated area of each groundwater potential

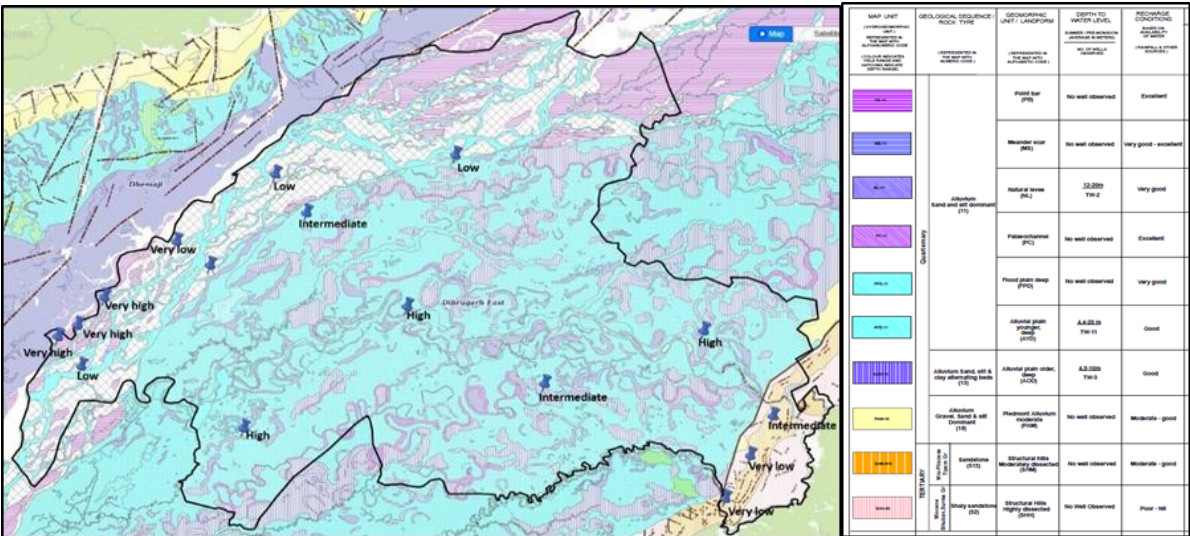


Fig 13: Hydro-geomorphological map with the legends

5. Conclusion

Groundwater potential zone map is prepared using eight thematic layers viz., geology, geomorphology, drainage density, landuse landcover, lineament density, slope, soil and aquifer depth. The weighted overlay analysis grouped the groundwater potential zone into five classes; very poor, poor, intermediate, high and very high with the highest percentage of area covered by very poor groundwater potential. Very poor groundwater potential zone falls in the highly urbanized area. The results is validated with the hydro-geomorphological map of Bhuvan NRSC and validation comes with a higher accuracy. The study reveals that the groundwater condition of the study area is in a safe position. To maintain the safe position of the groundwater prospect, monitoring and proper management in extraction is needed. Artificial recharge can be done in high and very high-prospect areas if required.

Credit authorship contribution statement

Bijoy Krishna Chetia: Conceptualization, Methodology, Data curation, Writing – review and editing, Validation; **Jayashri Dutta:** Conceptualization, Methodology, Formal analysis, Data curation, Visualization, Writing - original draft, Writing – review and editing, Validation; **William Narzary:** Methodology, Data curation, Formal analysis, Visualization.

Acknowledgement

The authors would like to gratefully acknowledge the Mission Director, Jal Jeevan Mission, Assam for his support in carry out this work as the work is a part Jal Jeevan Mission, Assam source sustainability program.

Funding information and conflict of interest

This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors. The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- Agarwal E, Agarwal R, Garg RD, Garg PK (2013) Delineation of groundwater potential zone: An AHP/ANP approach, *Journal of Earth System Science*. 122(3):887–898. <https://doi.org/10.1007/s12040-013-0309-8>
- Arulbalaji P, Padmalal D, Sreelash K (2019) GIS and AHP Techniques Based Delineation of Groundwater Potential Zones: a case study from Southern Western Ghats, India, *Scientific Reports*. 9(1):1–17. <https://doi.org/10.1038/s41598-019-38567-x>
- Biswas A, Arkoprovo B, Adarsa J, Prakash SS (2012) Delineation of Groundwater Potential Zones using Satellite Remote Sensing and Geographic Information System Techniques: A Case study from Ganjam district, Orissa, India, *Research Journal of Recent Sciences*. 1(9), 59. www.isca.in
- Krishnamurthy J, Venkatesa Kumar N, Jayaraman V, Manivel M (1996) An approach to demarcate groundwater potential zones through remote sensing and a geographical information system, *International Journal of Remote Sensing*. 17(10):1867–1884. <https://doi.org/10.1080/01431169608948744>
- Machdar I, Zulfikar T, Rinaldi W, Alfiansyah Y (2018) Assessment of groundwater vulnerability using DRASTIC Model and GIS : A case study of two sub-districts in Banda Aceh city, Indonesia, *IOP Conference Series: Materials Science and Engineering*, 334(1). <https://doi.org/10.1088/1757-899X/334/1/012032>
- Magesh NS, Chandrasekar N, Soundranayagam JP (2012) Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. ,*Geoscience Frontiers*. 3(2):189–196. <https://doi.org/10.1016/j.gsf.2011.10.007>
- Murmu P, Kumar M, Lal D, Sonker I, Singh SK (2019) Delineation of groundwater potential zones using geospatial techniques and analytical hierarchy process in Dumka district, Jharkhand, India, *Groundwater for Sustainable Development*, 9 (June) 100239. <https://doi.org/10.1016/j.gsd.2019.100239>

- V SP, MSS N, RS A (2024) Delineation of groundwater potential zones using remote sensing and Geographic Information Systems (GIS) in Kadaladi region, Southern India. *Journal of Groundwater Science and Engineering*, 12(2): 147-160. <https://doi.org/10.26599/JGSE.2024.9280012>
- Upadhyay RK, Tripathi G, Đurin B, Šamanovi'c S, Cetl V, Kishore N, Sharma M, Singh SK, Kanga S, Wasim M (2023) Groundwater Potential Zone Mapping in the Ghaggar River Basin, North-West India, Using Integrated Remote Sensing and GIS Techniques, *Water* . 15 (961). <https://doi.org/10.3390/w15050961>
- Wei A, Bi P, Guo J, Lu S, Li D (2021) Modified DRASTIC model for groundwater vulnerability to nitrate contamination in the Dagujia River basin, China, *Water Science and Technology: Water Supply*. 21(4): 1793–1805. <https://doi.org/10.2166/WS.2021.018>



Hydrogeomorphological Studies for Groundwater Prospecting using IRS -1D, LISS III Image in parts of Agra District, UP, India

Liaqat A.K.Rao and Ruby Siddiqui

Department of Geology, Aligarh Muslim University, Aligarh 202002, India
E-mail: jakraolak@yahoo.co.in, rubysiddiqui99@yahoo.co.in

Abstract

Hydrogeomorphological studies have been carried out in parts of Agra district U.P, India using IRS-1D, LISS III data for groundwater prospecting. The present investigation is aimed to assess and delineate groundwater potential zones for developments and exploration with the help of geomorphologic units and other associated features. The identified hydrogeomorphic units and features by remote sensing data and conventional information's and limited ground truth are alluvial plain, flood plain, flood prone area/paleochannels and ravines etc. The groundwater potential of each geological and geomorphologic unit has been evaluated in order to obtain a complete hydrogeological picture of Agra district.

Introduction

Agra district of Uttar Pradesh located along southern fringe of the indo-gangetic plain face severe scarcity of ground water. The available surface water resources are inadequate to meet entire water requirement for different purposes. The demand for underground water has increase by every year.

In recent years extensive use of satellite remote sensing has made it easier to define the demarcation and delineation of different groundwater potential zones based in geomorphology and their associated features. The remote sensing technique has proved to be an effective tool for groundwater studies. Studies are being carried out in this direction by many workers Saraf and Choudhary 1998, Prakash and Misra 1993, Ravindram and Jeyram 1997, Thomas et al 1995, Prithavi Raju, 1980.

Study Area

The area under study Agra district is a part of indo-gangetic alluvial plain lies between north latitudes of 26 44' and 27 25' and east longitudes 77 26' and 78 32' covering an area of about 4027 sq.km. (Fig.1)

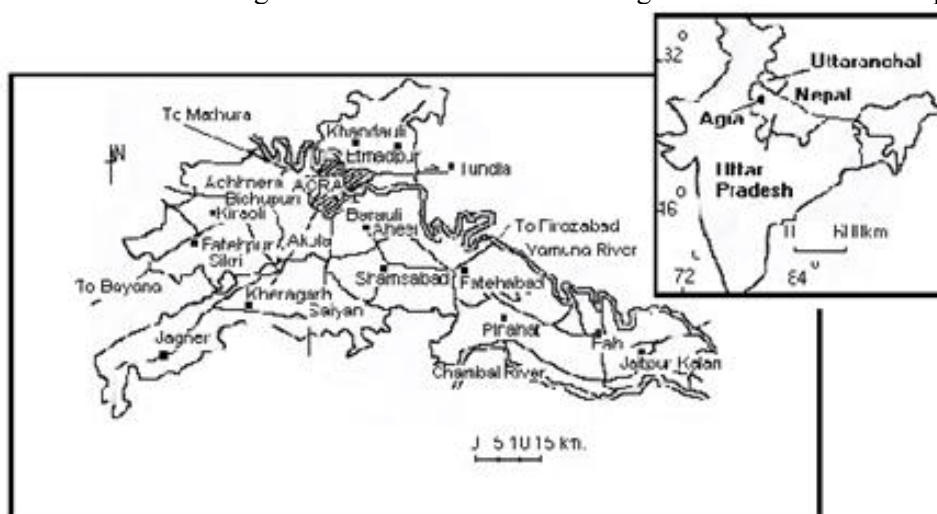


Figure 1: Location Map of Agra District, Uttar Pradesh

Physiography

Physiographically Agra district is divided into five physical divisions via; khadar lowlands, trans-yamuna plain, yamuna uplands, southwestern uplands and the yamuna – chamber ravines of the two major physiographical divisions of India (Peninsular region and the Great Indo-Gangetic Alluvial Plains).

Drainage

The three perennial streams in the area are yamuna, Utangan and the Chambal. the river Yamuna and its tributaries drain the region and follows the general slope and relief features and adopt the direction roughly N W to SE.

Climate

The study area lies in the region of tropical monsoon climate which is influenced by the two distinct air currents known as the NE and the SW monsoon which are further subdivided as:

The season of NE monsoon

- (1) Cold weather season (Jan-feb)
- (2) Hot weather season (march-mid June)

The season of SW monsoon

- (1) The season of general rain (mid June-mid Sept)
- (2) The season of retreating monsoon (mid Sept-mid Dec)

The mean annual rainfall ranges between 600 and 650 mm.

Soil

The soil of the region is alluvial and geologically it may be place into two types namely as khaddar and Bhangar. The soil of the district Agra is further categorized into five types as sandy soil, sandy loams, loamy soil, clayey loams and clayey soils.

Database:

IRS -1D,LISS III geocoded standard false color composite, a combination of three spectral bands 2, 3 and 4 on 1:50,000 scale, March 2003, data have been used in the present study.

Geological setup:

The study area is a part of Indo-Gangetic plain and major part of the area is covered by Gangetic alluvial deposit of the Quaternary period mainly comprises gravel, sand, silt, clay and kankar overlying the rocks belonging to the Vindhyan Super Group. The geological sequence of the area based on the work carried out by Heron (1922) is given below and follow in the present work.

Quaternary	Recent to Upper Pleistocene	- Younger alluvium
	Pleistocene	- Older alluvium Laterite and clay
.....Unconformity.....		
Precambrian	Upper Vindhyan	Upper Bhandar sandstones Lower Rewa sandstones

The lower Rewa sandstone occurs as discontinuous stake ridge southwest of Bayana and are hard, compact, fine grained, bedded white to pinkish in color and less ferruginous that of overlying upper Bhander sandstone .The upper Bhander sandstone exhibits shale I intercalation at different levels. The sandstone is reddish in color with characteristic white to fawn colour spots.

The study area comprises a large amount of alluvium deposit occurs as lenticular beds and show rapid variation both horizontally and vertically and essentially composed of sand silt, clay and gravel. On satellite image IRS -1D, LISS III, this unit is identified by its white tone and medium.

Geomorphology:

Geomorphologic units and other associated features have been identified and mapped through visual interpretation from IRS-1D LISS III image. The hydro geomorphic unit's viz., ravenous land, sand bar (river sand), paleochannels, younger alluvium, recent flood plain and older undulating surfaces have been identified and mapped along the river Yamuna of the study area through visual interpretation, are briefly discussed and illustrated in Fig (2).

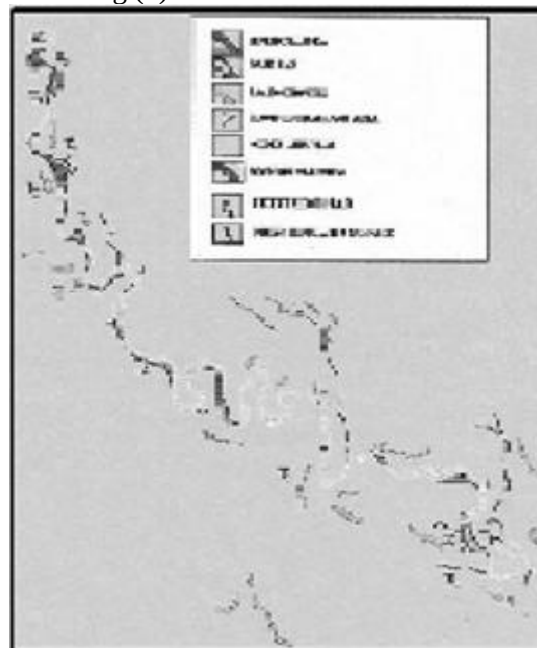


Figure-2: Hydrogeomorphological Map of Agra district along Yamuna River

Ravenous Land: The ravenous land formed as a result of intense gulling and certain upliftment of the area affecting unconsolidated material results in the formation of perceptible channels. The ravines are dominantly present on either side of the Yamuna and Chambal rivers. The ravines are identified on IRS-1D, LISS III images by their light-yellow tone, coarse texture and elongated shape with dendritic drainage pattern.

Sand Bar (River Sand): Abundant longitudinal sand bar and point bar have been identified along the river Yamuna. The sand is well-sorted and well-rounded represent the alluvium stored temporarily along the river channel. Sand bar is identified by light blue tone, fine texture and lenticular to elongated shape. These sand bodies are normally flooded during the monsoon and during dry season, however, they serve as highly fertile piece of land for cultivation. The extremely shallow water table excludes the need of irrigation. The groundwater conditions are good and fresh water extends to considerable depth below the surface.

Paleochannels: Paleochannels are old river courses buried by subsequent sedimentation and identified on IRS-1D, LISS-III images by their contrasting dark tone in a characteristic winding fashion in association with cropping pattern. The paleochannels are generally potential reservoirs for groundwater exploration and their identification is useful in flood mitigation. Several paleochannels are identified

adjacent to the Yamuna river course on either side. The soil in these paleochannels has more moisture content as compared to the adjacent areas due to groundwater flow in these paleochannels. Groundwater prospects in these buried channels appear to be excellent because of hydrophilic nature of alluvium, retention of flood water, presence of vegetations and shallow to very shallow water table.

Younger Alluvium: The younger alluvium refers to the recent alluvium, deposited by the rivers and mainly confined to the vicinity of the main river channels. The younger alluvium is identified by its characteristic dark red tone due to presence of high moisture content and abundant vegetation. Most of the parts of the younger alluvium coincide with younger terraces (To), which are the recent flood plain of the river Yamuna and is maintained and modified each year by the floods.

Older Alluvium: The older alluvium is upland area lying at some distance from the main river channel. This unit is characterized by deep water table and also not reachable by the flooded water. This unit is widely marked by the wastelands in the form of saline land and ravenous land along the river Yamuna and their tributaries.

Older Undulating Surface: The land which is devoid of forest and vegetative cover occupies relatively higher topographic location is identified as old undulating surface (Ti) by its light yellow to greenish blue colour, fine to mottled texture and irregular shape near Fatehabad and Bah tehisils of Agra district.

The various geomorphic units and their ground water bearing prospects are summarized and are given in Table-I

Table I- Groundwater prospects of various geomorphic units

Geomorphic Units	Description	Water Prospects
Older alluvium	Characterized by deep water table, wastelands, (Saline land and ravenous land) not reachable by flooded water	Moderate to poor
Older undulating Surface (T1)	High topography, undulating surfaces devoid of forest comprising mainly silt and clay with minor sand	Poor
Ravenous land	Comprising mainly silt and clay with intense gulling	Poor
Sand bar (river sand)	Undulating plain comprising sand silt and clay. Sand is dominant.	Good
Paleochannel	Channels which are cut off from main course of the river which are buried or abounded comprises of sand, silt and clay	Very good
Younger alluvium	Deposited by the rivers maintained and modified every year consisting of clay silt and coarse sand of varying litho logy	Very good

Conclusion

Remote sensing technology is very useful for the geomorphologic mapping and ground prospective areas mapping and management. The information can be generated on prospects, quality and depth wise, which will help the planner and decision makers for implementing fruitful ground water development plans.

Acknowledgement

The authors are thankful to Prof.M.Raza,Chairman,Department of Geology,A.M.U for providing facilities to carry out this work. Thanks are also due to CST,U.P.for providing financial assistance.

References

- Heron, A.M., (1922). The Gwalior and Vindhyan System in south-eastern Rajputana. Mem.Geol.Surv.India, 45(2) pp.120-180.
- Prakash,S.Ravi and Misra,D (1993). Identification of groundwater prospective zones byusing remote sensing and geoelectrical methods in and around Saidnagar area,Daker block,Jalaun District,U.P.Ind.Soc.Remote Sensing,21(4)pp.2127-227.

- Prithavi Raju N (1980). Geomorphic studies in Sarada river basin, Vishakhapatnam district, Andhra Pradesh, India. Ph.D thesis Andhra University, Vishakhapatnam, India.
- Ravinderanm K.V and Jeyaram A (1997). Groundwater prospects of Shahbad Tehsil, Bayana District, Eastern Rajasthan. A Remote Sensing Approach. Ind.Soc.Remote Sensing, 25(4) pp.239-246.
- Saraf, A.K. and Chaudhary, P.R (1998). Integrated remote sensing and GIS for groundwater exploration and identification of artificial recharge sites. Inter.Jour.Remote Sensing, 19(10) pp.1824-1841.
- Thomas Verma, V.K., Sood, A., Litoria, P.K., Sharma, P.K and Ravindran, K.V (1995): Hydrogeology of Talwandi Sabo Tehsil, Bhatinda District, Punjab. A Remote Sensing Approach. Ind.Soc.Remote Sensing, 23(2) pp.47-56.