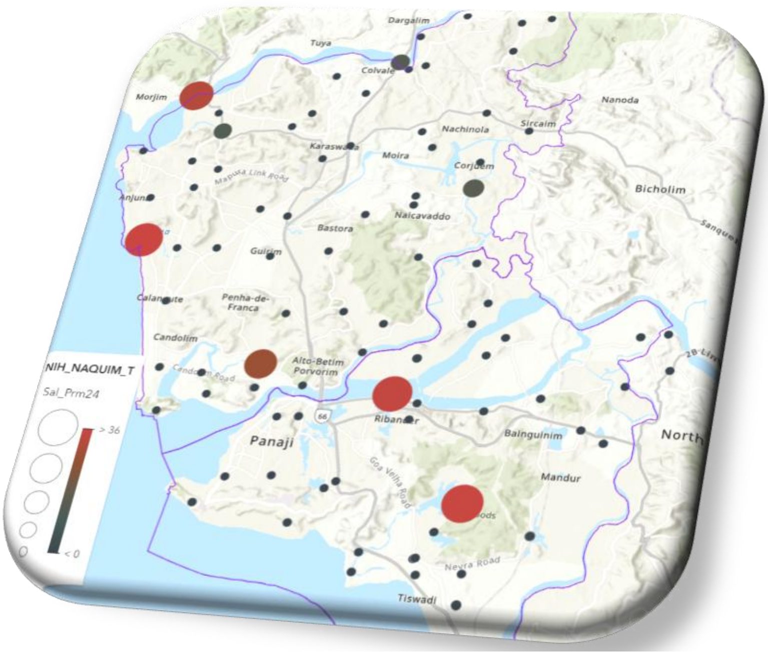
Report No.: NIH/TR/2025-26/##
Final Report

Coastal Salinity Study in Bardez and Tiswadi Taluks, North Goa District, Goa State



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National Institute of Hydrology
Deptt. of WR, RD & GR,
Ministry of Jal Shakti, Govt. of India
Jal Vigyan Bhawan, Roorkee - 247667 (Uttarakhand), INDIA

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FOREWORD

In the coastal regions of India, where freshwater aquifers are at the forefront of competing pressures from urbanization, tourism, climate change, and the advancing influence of saline water from the sea and tidal rivers, groundwater acts as the lifeline of millions residing in the coastal regions. Currently, the sustenance of this water is more critical and under priority than ever.

The National Institute of Hydrology has long been committed to providing the scientific foundation upon which sound water resource management decisions can be made. It is in this spirit that NIH, Hard Rock Regional Centre, Belagavi, has enthusiastically joined hands with the Central Ground Water Board, South Western Region, Bengaluru, in the NAQUIM 2.0 programme for the coastal taluks of Bardez and Tiswadi in North Goa, a region that is simultaneously one of India's most vibrant tourism destinations and one of its most hydrogeologically vulnerable coastal settings.

This Inception Report presents the first systematic stable isotope-based investigation of saline water ingress in the coastal aquifer system of North Goa, drawing upon field data from 89 observation wells sampled across two seasons and analyzed at the Nuclear Hydrology Laboratory of NIH, Roorkee. The study establishes, for the first time, the isotopic fingerprint of groundwater recharge and saline mixing in this region which is a contribution that transcends the immediate objectives of NAQUIM 2.0 and lays the scientific foundation for all future hydrogeological investigations in the North Goa coastal zone.

I am assertive that the findings presented herein including the identification of wells actively affected by saline intrusion, the delineation of seasonally vulnerable and safe aquifer zones, and the establishment of the Local Groundwater Line for the study area will provide CGWB and allied agencies with the evidence base needed to design targeted, effective and lasting groundwater management interventions.

I commend the dedicated efforts of the NIH team at Belagavi and Roorkee, and express sincere appreciation to CGWB SWR, Bengaluru, and the SUO, Belagavi, for their invaluable collaboration and support throughout this study.

Dr. Y. R. S Rao
Director

PREFACE

The coastal aquifers of North Goa are under siege — quietly, season by season, as the relentless demand for freshwater from an expanding urban population and a globally renowned tourism industry draws down the very groundwater reserves that sustain them. It was with an awareness of this slow but accelerating crisis that the NIH team at Belagavi took up the collaborative study with CGWB, State Unit Office Belagavi of CGWB South Western Region, Bengaluru, under the NAQUIM 2.0 programme for Bardez and Tiswadi taluks.

What makes this study distinctive is not merely the scale of field sampling that is 89 observation wells across 478 sq. km, sampled across two seasons, but the scientific approach brought to a region that had previously not been examined through the environmental isotope hydrology. Stable isotopes of oxygen and hydrogen are nature's own tracers, carrying within each water molecule an irreplaceable record of its journey from rainfall to recharge to the aquifer. Reading that record across a coastal salinity gradient tells us, with a precision no conventional field instrument can match, where saline water is entering, by which pathway, and how far it has travelled.

The field campaigns were carried out with the active cooperation of well owners, local communities and CGWB officials across both taluks, often in difficult pre-monsoon conditions. The isotope analyses were conducted at the Nuclear Hydrology Laboratory of NIH, Roorkee, whose precision and reliability are reflected in the quality of the dataset presented in this report.

The findings confirm both what we feared and what we hoped: saline intrusion is real, measurable and spatially concentrated, but large portions of the aquifer remain fresh and recoverable, provided prompt and well-directed management action is taken. It is our sincere hope that this report serves as a scientific compass for those charged with that responsibility.

Dr. Abhilash R	**Dr. Tripti M**	**Dr. B. Venkatesh**	**Dr.Jyoti P Patil**	**Smt. Sushamita Wadde**
Scientist-C and PI	**Scientist-D & Co-PI**	**Scientist-G & Co-PI**	**Scientist-E & CoI**	**Scientist-B & CoI**

EXECUTIVE SUMMARY

1. Rationale

Coastal aquifers represent one of the most sensitive and scientifically complex freshwater systems on the planet. In the context of India's rapidly expanding coastal urbanization and tourism economy, the threat of saline water intrusion into shallow phreatic aquifers poses an increasingly critical challenge to freshwater availability, public health and long-term groundwater sustainability. Bardez and Tiswadi taluks in North Goa District exemplify this challenge: they encompass the state capital of Panaji, the globally recognized beach resort belt of Calangute, Candolim, Baga and Anjuna, and the hydraulically complex estuarine systems of the Zuari, Mandovi and Chapora rivers, all within a hydro-geologically vulnerable lateritic aquifer setting characterized by shallow water tables, seasonal groundwater depletion and direct connectivity with tidal water bodies.

Per capita freshwater availability in Goa has declined sharply from approximately 4,500 m3 per capita in 1980 to around 2,200 m3 at present, and the coastal belt faces a documented daily water supply deficit of 85 million litres. The state receives nearly 8 million tourists annually, and 37% of hotels in the coastal zone rely on groundwater, a dependence that intensifies seasonal abstraction stress precisely when the aquifer is most vulnerable to saline ingress. Despite these pressures, no systematic, isotope-based scientific assessment of saline water intrusion had been conducted in the study area prior to the present investigation. This absence of baseline hydrogeological evidence has been a critical gap preventing the design of targeted, evidence-based groundwater management strategies for this hydro-geologically stressed and economically vital coastal region.

2. Objectives

The National Institute of Hydrology (NIH), Hard Rock Regional Centre, Belagavi, was formally invited by the Central Ground Water Board (CGWB), South Western Region, Bengaluru, to collaborate in the NAQUIM 2.0 study for Bardez and Tiswadi taluks under the Annual Action Plan (AAP) 2024-25. The specific objectives entrusted to NIH under the collaboration are:

a) To carry out stable isotope sampling and analysis ($d^{18}O$ and $d^{2}H$) from key observation wells to identify the origin and processes of saline water ingress in the coastal aquifer system.

b) To assess the status and spatial distribution of saline intrusion through isotopic mapping, in integration with hydrochemical and hydrogeological data.

c) To characterize the lateral extent of saline influence and distinguish between tidal river-driven and direct seawater-driven salinity mechanisms.

3. Methodology

The investigation adopted a systematic, multi-phase approach integrating pre-field GIS-based planning, comprehensive field sampling across two seasons, and stable isotope laboratory analysis at the Nuclear Hydrology Laboratory, NIH, Roorkee.

Field Sampling Network: A 5 km x 5 km grid was overlaid on the 478 sq. km study area to ensure uniform spatial coverage. Through extensive field reconnaissance, 89 key observation wells were identified and sampled, complemented by surface water samples from the Zuari, Mandovi and Chapora rivers, tidal tributaries and lake water bodies to establish hydrochemical end-members.

Seasonal Sampling: Comprehensive sampling was conducted during both the pre-monsoon (March-May 2024), representing peak groundwater stress and maximum saline intrusion risk and the post-monsoon (October-November 2024), reflecting the state of the aquifer after monsoon recharge. This two-season design enables assessment of both the maximum extent of saline influence and the seasonal recovery capacity of the aquifer.

In-situ Measurements: At each well, critical field parameters were measured on-site: electrical conductivity (EC), total dissolved solids (TDS), salinity, pH, dissolved oxygen (DO), oxidation-reduction potential (ORP), temperature and depth to water level (DTWL).

Stable Isotope Analysis: Water samples were dispatched to the NIH isotope laboratory at Roorkee, where $\delta^{18}O$ and $\delta^{2}H$ were determined by Isotope ratio mass spectrometer (IRMS) connected with water equilibration system supplied by Elementar, with results reported against the V-SMOW standard. Deuterium Excess (d-excess = $\delta^{2}H - 8 \times \delta^{18}O$) was computed as a diagnostic parameter for evaporation and saline mixing assessment.

Spatial Analysis: IDW/Kriging interpolation in GIS was applied to all hydrochemical and isotopic parameters to generate spatial distribution maps delineating fresh, transitional and saline-influenced groundwater zones across the study area.

4. Analysis and Results

The present study establishes, for the first time, a comprehensive isotopic and hydrochemical baseline for the coastal aquifer system of Bardez and Tiswadi taluks -- constituting the most extensive groundwater investigation ever conducted in North Goa.

The principal results are summarized below:

i) Groundwater levels: Mean seasonal water table rise of 1.05 m between pre-monsoon and post-monsoon seasons confirms active monsoon recharge. Majority of wells have DTWL less than 5 m bgl, reflecting high saline intrusion susceptibility in shallow lateritic aquifers.

ii) Hydrochemical evidence of saline intrusion: Pre-monsoon EC reached a maximum of 2,890 uS/cm (3.9 times the BIS drinking water limit of 750 uS/cm), TDS a maximum of 1,477 mg/L (2.9 times the BIS acceptable limit of 500 mg/L), and salinity a maximum of 1.5 ppt (brackish classification). Approximately 12-15% of wells exceeded the BIS potable threshold during the pre-monsoon season.

iii) Isotopic confirmation of saline mixing: Pre-monsoon d18O values ranged from -2.543 to +0.78 per mil V-SMOW (mean -1.61 per mil). The maximum of +0.78 per mil approaches the seawater isotopic composition (~0 per mil) and confirms seawater mixing fractions of up to 25-35% at the most affected wells. The observed isotopic range is substantially wider than all earlier Goa groundwater datasets, confirming the scientific value of the expanded 89-well network.

iv) Dominant salinity mechanism tidal rivers: The positive correlation between EC and d18O, combined with bivariate isotope plot analysis, confirms that the primary driver of inland groundwater salinization is tidal backwater ingress via the Zuari, Mandovi and Chapora estuaries rather than direct open-sea intrusion at the shoreline. This critical distinction has direct consequences for the targeting of management interventions.

v) Local Groundwater Line (LGWL) established: The best-fit regression for all groundwater samples across both seasons ($\delta^2H = 5.26 \times \delta^{18}O + 4.32$; $R^2 = 0.73$; $n = 178$) defines the LGWL for Bardez and Tiswadi is a first-of-its-kind isotopic reference line for North Goa, available for all future hydrogeological investigations.

vi) Well classification into three categories: Systematic classification of all 89 wells yielded: Category I (Actively Affected, 10 wells, 11.2%), wells with confirmed, persistent saline intrusion including wells 73 and 70 with $\delta^{18}O > 0$ confirming direct marine mixing; Category II (Seasonally Vulnerable, 10 wells, 11.2%), wells with seasonal saline influence, including a critical alert for wells 33 and 27 where post-monsoon EC exceeded pre-monsoon EC, indicating escalating deterioration; and Category III (Fresh, 69 wells, 77.5%), predominantly inland and north-eastern plateau wells with consistently safe groundwater quality.

vii) Fresh groundwater storage: The close correspondence of post-monsoon d-excess values (mean 10.34 per mil) with the GMWL value of 10 per mil confirms that North Goa coastal aquifers store predominantly fresh groundwater recharged on an annual monsoon cycle, making them highly responsive to both recharge augmentation and sensitive to monsoon variability under climate change.

5. Significant Outcomes and Utility for Water Resources Management

The scientific outputs of this investigation translate directly into the following management-relevant outcomes:

Identification of safe aquifer zones: The north-eastern sector of the study area consistently shows the freshest, most isotopically depleted groundwater in both seasons and is identified as the primary safe aquifer reserve for drinking water supply development in North Goa. This finding provides CGWB with a scientifically defensible basis for locating new water supply wells and protecting existing recharge zones from urban encroachment.

Management of saline intrusion: The differentiation between tidal river-driven and direct seawater-driven salinity mechanisms directs management interventions towards the estuarine buffer zone rather than the shoreline alone. Artificial recharge structures positioned along the inland margin of the Zuari, Mandovi and Chapora tidal zones will be most effective in augmenting the freshwater head and counteracting saline ingress in the largest number of affected wells.

Early warning for vulnerable wells: The identification of wells 33 and 27 as actively worsening with post-monsoon EC exceeding pre-monsoon EC provides an early warning signal that targeted abstraction regulation and immediate managed recharge at these locations is essential to prevent transition from Category II to Category I status.

Scientific foundation for NAQUIM 2.0 management plan: The integrated isotopic and hydrochemical dataset provides the evidence base for the aquifer management plan being prepared by CGWB, including demarcation of safer aquifer pockets for drinking water, recommendation of artificial recharge structures, abstraction regulation zones and groundwater quality management interventions. The established LGWL and seasonal isotopic baseline will serve as the reference framework for all future monitoring and assessment in the study area.

Contribution to national groundwater science: This study fills a fundamental gap in the scientific literature on coastal aquifer salinization in India's west coast region. The multi-parameter, two-season, 89-well dataset is the first of its kind for North Goa establishes a replicable scientific protocol for isotope-based coastal aquifer assessment that can be extended to other NAQUIM 2.0 priority areas along India's 7,516 km coastline.

Tourism and urban water security: Given that the study area supports India's largest international beach tourism economy and a daily water deficit of 85 million litres, the science-based identification of freshwater zones and saline intrusion hotspots directly supports the planning of water supply infrastructure, sustainable tourism development and climate adaptation strategies for one of India's most water-stressed coastal regions.

Keywords: *Coastal aquifer salinization; Stable isotope hydrology; NAQUIM 2.0; Tidal river influence; Groundwater management*

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1 INTRODUCTION

1.1 Background

Groundwater is a critical freshwater resource in India, providing sustenance to millions of households, agricultural operations and industrial units. In coastal regions, the sustainability of groundwater resources is particularly vulnerable to the twin pressures of increasing abstraction and the process of saline intrusion from adjoining marine and estuarine systems. Scientific assessment of coastal aquifer dynamics is therefore essential for informed groundwater management and long-term water security.

1.1.1 National Aquifer Mapping and Management Programme (NAQUIM)

The National Aquifer Mapping and Management Programme (NAQUIM) is a flagship programme of CGWB under the Ministry of Jal Shakti, Government of India, aimed at systematic delineation and characterization of aquifers and preparation of aquifer management plans. NAQUIM 2.0, initiated from April 2023 after successful completion of NAQUIM 1.0, enhances the programme by: increasing the density of dynamic groundwater data; generating issue-based scientific inputs down to the Panchayat level; formulating implementable management strategies; and ensuring enhanced participation of State agencies. Under AAP 2024–25, CGWB SWR Bengaluru has planned NAQUIM 2.0 studies in the coastal taluks of Bardez and Tiswadi, North Goa as a priority area owing to saline ingress concerns.

1.1.2 Collaboration with NIH

CGWB formally invited NIH, Hard Rock Regional Centre, Belagavi (letter dated 01.03.2024) to collaborate on three specific technical components: **(g)** Isotope sampling and analysis, **(h)** Bromide sampling and analysis, and **(i)** Mapping of saline intrusion including lateral and vertical extent.

After due deliberation, it was mutually agreed that the bromide sampling and analysis component would not form part of NIH's scope of work under the present study, as the investigation would be comprehensively addressed through stable isotope and other hydro-chemical methods.

1.1.3 Scientific Rationale for Isotope Studies

Conventional hydro chemical indicators (EC, TDS, and chloride) indicate salinity presence but cannot distinguish its origin direct seawater intrusion, tidal/estuarine influence, evaporation concentration, or irrigation return flows. Stable isotope analysis (δ^2H, $\delta^{18}O$) as a conservative tracer provide the necessary evidence to differentiate sources, understand mixing dynamics, identify recharge mechanisms, and delineate saline intrusion zones directly supporting site-specific management interventions under NAQUIM 2.0.

1.1.4 Purpose of this study

This study documents NIH's scientific framework and field activities: isotope sampling from 89 groundwater wells, in-situ measurements of pH, DO, EC, TDS and salinity, and surface water sampling from rivers and hydraulically influencing water bodies. Pre-monsoon and post-monsoon datasets together provide the basis for assessing seasonal variability and mapping saline influence in the study area.

2 LITERATURE REVIEW

Coastal aquifer salinization is a globally recognized hydrogeological challenge, with significant implications for freshwater availability, ecosystem health and socio-economic development. The problem assumes heightened importance in rapidly urbanizing, tourism-intensive coastal regions where freshwater demand is disproportionately high relative to the natural replenishment capacity of aquifer systems. The Bardez and Tiswadi taluks of North Goa represent precisely such a setting, where the interplay of lateritic geology, tidal river systems, seasonal groundwater dynamics and intense anthropogenic pressures creates a complex and scientifically challenging coastal hydrogeological environment. This section reviews the relevant scientific literature on saline water intrusion in coastal aquifers, organized under international studies, national studies within India, and the identification of critical research gaps in the specific context of the study area.

2.1 International Studies on Saline Water Intrusion in Coastal Aquifers

2.1.1 Foundational Framework: Seawater Intrusion and the Ghyben-Herzberg Principle

The scientific understanding of seawater intrusion into coastal freshwater aquifers is rooted in the Ghyben-Herzberg relationship, which describes the hydrostatic equilibrium between freshwater and saltwater in an unconfined coastal aquifer. This classical concept, established in the late nineteenth century, forms the theoretical basis for understanding the position of the freshwater-saltwater interface and its response to changes in freshwater head caused by groundwater abstraction or recharge variability. Subsequent refinements, including the work of Hubbert (1940) and Bear (1979), established the dynamic nature of the interface as a transition zone rather than a sharp boundary, a concept that has fundamental implications for isotope-based investigations.

The role of environmental tracers in groundwater studies was conceptually established by Craig (1961), who defined the Global Meteoric Water Line (GMWL) by demonstrating a linear correlation between deuterium (δ^2H) and oxygen-18 ($\delta^{18}O$) in meteoric waters worldwide. This foundational contribution established the isotopic framework within which deviations from the GMWL could be interpreted as evidence of evaporation, mixing with evaporated water or marine influence, providing the basis for all subsequent isotope-based investigations of coastal aquifer salinization.

2.1.2 Isotope Hydrogeology and Source Identification of Coastal Salinity

A major body of international research has demonstrated the indispensable role of stable isotopes in differentiating the sources and mechanisms of coastal groundwater salinization, particularly where conventional hydrochemical analysis alone is insufficient.

Investigations in coastal aquifers of Greece have used the stable isotopic composition of $\delta^{18}O$ and $\delta^{2}H$ in combination with hydrogeological and hydrochemical data to characterize complex interactions among surface waters, groundwaters and coastal lakes. A notable study in northeastern Greece demonstrated that the elevated salinity of a coastal aquifer was not attributable to direct seawater intrusion but rather to brackish lake water intrusion induced by intensive groundwater pumping for irrigation, a conclusion that could only be reached through isotopic analysis rather than conventional geochemistry alone (Matiatos and Alexopoulos, 2011). This highlights the critical discriminatory power of isotopes in identifying the true source of salinity.

In Baja California, Mexico, a coastal tourist destination heavily dependent on a single aquifer for drinking water and agricultural needs, a comprehensive investigation using deuterium, oxygen-18, carbon-14 and gaseous tracers established that groundwater salinization in the lower coastal plain was a result of both irrigation return flows and seawater intrusion, with evaporation playing a significant role in modifying the isotopic signature (Hernández-Antonio et al., 2015). The parallels with Goa's coastal tourism-dependent setting are directly relevant, particularly the combination of intensive pumping, evaporative enrichment and marine influence.

Studies conducted in China's coastal aquifers have provided important insights into the multiaquifer dynamics of saline intrusion. Research on Donghai Island demonstrated that isotopic signatures of $\delta^{18}O$ and $\delta^{2}H$ are essential to distinguish recharge sources between shallow and deep aquifer systems, and to identify the seasonal mixing between fresh recharge, irrigation return flows and seawater components (Liu et al., 2023). In the Laizhou Bay coastal plain of China, a combined chemical and isotopic investigation established the evolution pathways of groundwater salinisation and the progression of the freshwater-saltwater transition zone (Han et al., 2014). These studies emphasise the importance of integrating isotopic data with seasonal hydrochemical monitoring precisely the methodology adopted by NIH in the present study.

In the context of tidal aquifer systems directly analogous to Goa's Mandovi and Chapora estuarine settings investigations in the Arani-Koratallai basin near Chennai demonstrated how stable isotopes provide insights into the mixing processes of freshwater, evaporated surface water and marine components, including the identification of the influence of managed aquifer recharge structures on isotopic signatures (Post et al., 2012). The use of Cl/Br ratios in combination with $\delta^{18}O$–$\delta^{2}H$ data in Spain and Portugal proved effective in tracing salinity origins in diverse geological settings (Alcala and Custodio, 2008), an approach of direct relevance to the isotope integrated methodology being employed in the present Goa study.

2.1.3 Coastal Groundwater Stress in Tourism-Intensive Regions

International research has increasingly focused on the intersection of tourism, urbanization and coastal groundwater stress. Roughly half of the world's population currently experiences severe water scarcity for at least part of the year (UN World Water Development Report, 2024), and this stress is disproportionately concentrated in coastal tourism zones where per capita water demand is substantially elevated relative to resident populations.

Studies in Mediterranean coastal destinations, the Caribbean, and Southeast Asian tourism zones consistently report that hotel and resort water consumption is two to four times higher per occupant than domestic residential use, placing severe stress on shallow coastal aquifers and exacerbating the rate of seawater intrusion. In La Paz, Baja California a coastal tourist destination intensive aquifer exploitation for tourism and agriculture resulted in groundwater table declines of up to 10 m and TDS values reaching 5,800 mg/l, conditions approaching those observed in stressed North Goa coastal areas. A global review by Klassen and Allen (2017) identified that tourism-driven groundwater abstraction is one of the most under documented yet significant drivers of coastal saline intrusion, and that isotope-based studies are critical for establishing the baseline understanding required for effective management.

2.2 National Studies on Saline Water Intrusion in India

2.2.1 Overview of Coastal Saline Intrusion in India

India has an extensive coastline of approximately 7,516 km encompassing nine coastal states and four union territories, with coastal aquifer systems hosting a significant proportion of the country's freshwater resources. Prusty and Farooq (2020), in a comprehensive national review, documented that seawater intrusion has been reported along the coastal areas of Gujarat, Maharashtra, Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, Odisha and West Bengal. However, the review notably highlighted that Goa, despite its extensive coastal exposure, was at that time classified as having all administrative units in the 'safe' groundwater category, reflecting an absence of comprehensive scientific documentation of saline intrusion rather than its actual absence. This is a critical observation that underlines the need for the present investigation.

At the national level, India is recognized as a water-stressed country. Per capita water availability in India has declined to approximately 1,486 cubic metres annually below the internationally recognized Falkenmark Water Stress Indicator threshold of 1,700 cubic metres per capita per year and projections indicate further decline to 1,191 cubic metres by 2050. The country supports nearly 18 per cent of the world's population but has access to only 4 per cent of global freshwater resources, making groundwater conservation and quality protection a matter of national urgency.

2.2.2 Isotope-Based Studies in Indian Coastal Aquifers

Environmental isotope investigations in Indian coastal aquifers have been concentrated in the peninsular coastal states of Tamil Nadu, Kerala, Karnataka and Andhra Pradesh, as well as in the eastern coast in West Bengal. These studies collectively demonstrate the superiority of isotope-based approaches over conventional hydrochemical methods for coastal aquifer characterisation.

One of the most comprehensive studies for the southern Indian coast was conducted in the Chennai coastal aquifer by Indu et al. (2015) and subsequent work by Post et al. (2012), who used $\delta^{18}O$, δD, Cl/Br ratios and managed aquifer recharge data to identify the dominant hydrogeochemical processes including seawater intrusion and saline evolution from intensive evaporation. The study found that heavy stable isotopes were dominant in the coastal zone due to seawater intrusion, with $\delta^{18}O$ values ranging from −5.6 to −2.9‰, and estimated that approximately 201 km^2 of coastal area was affected by salinisation. The study underscored the need for managed aquifer recharge and freshwater ridge maintenance as management responses measures that are equally relevant for Goa.

In coastal Karnataka, towards south of Goa, the detailed hydrochemical and isotopic studies have been carried out in the Nethravati-Gurupura and Swarna river basins covering Mangalore - Udupi stretches (Lambs et al., 2010; Tripti et al., 2013a & b, 2016, 2018; Gurumurthy et al., 2015). These findings suggested that along the shoreline, the groundwater had relatively heavier isotopic composition ($\delta^{18}O$ = -2 ‰) than further inland. Within few kilometers from the coast, the groundwater showed much lower isotopic composition similar to rainwater ($\delta^{18}O$ = -2 to -3 ‰) which indicated the active groundwater recharge by the pre-dominant summer monsoon rainfall.

A hydrogeochemical and isotopic investigation of shallow coastal aquifers in Udupi District revealed TDS values ranging from 40 to 12,100 mg/l and $\delta^{18}O$ values between −2.73‰ and −0.6‰, indicative of highly saline conditions in proximity to the coast. The study confirmed that saline water intrusion from seawater was a serious threat and demonstrated that approximately 50 per cent of samples showed evidence of brackish to saline conditions (Akshitha et al., 2021). Given the geological and hydrogeological continuity between the Karnataka coast and Goa, these findings have direct relevance for anticipating conditions in the study area.

The detailed isotopic study of groundwater, river water, spring and rainwater in the coastal region to Western Ghats stretch (covering Kerala, Karnataka and Tamil Nadu) have been reported earlier (Tripti et al. 2019, 2022). The study showed the significant effect of summer monsoon rainfall on the recharge of regional groundwater and surface water. The rainwater isotopic composition revealed that about 28% of rainfall originated from the continental moisture recycling along the southwest coast of India which further fed the groundwater and river water in the region. The rain, groundwater, river water and lake water of inland mountains in Ooty region showed cyclonic impact during winter monsoon season.

For the coastal Tamil Nadu aquifer system, isotopic investigations confirmed multiple recharge sources contributing to shallow groundwater variability, with enriched isotopic signatures in coastal areas indicating evaporative recharge and marine influence, while depleted signatures in inland areas reflected fresh meteoric recharge (Elumalai et al., 2022). This type of isotopic zonation across a coastal-inland transect is an expected feature of the Goa coastal aquifer system and is a primary objective of the current NIH investigation.

In eastern India, Shivanna et al. (1993) employed a suite of environmental isotopes including D, ^{18}O, ^{34}S, ^{3}H and ^{14}C to examine seawater salinity in the coastal part of West Bengal, demonstrating the value of multi-isotope approaches in resolving complex salinity mixing in tidal river environments. More recently, Kumar et al. (2022) integrated magnetic susceptibility, hydrogeochemical and isotopic data to assess seawater invasion in the coastal aquifers of Digha, West Bengal, providing a template for integrated coastal aquifer assessment that is directly applicable to the Goa study context.

Simulation and modelling studies have been conducted at several Indian coastal locations to understand seawater intrusion dynamics. Bhosale and Kumar (2002) used the SUTRA software for simulation in the Ernakulam coast of Kerala, establishing that the most sensitive zone for seawater intrusion lies within 400–2,000 m of the high tide line. Lathashri and Mahesha (2015) carried out simulation-optimisation modelling on the Karnataka sea-coast, and Sindhu et al. (2012) conducted similar work in Trivandrum, Kerala. These studies provide the computational framework within which the isotopic and hydrochemical field data from the present Goa study can eventually be integrated for predictive management planning.

2.2.3 Goa-Specific Groundwater Studies and Their Limitations

Despite its ecological and hydrogeological significance, published scientific literature on saline water intrusion in the coastal aquifers of North Goa particularly in Bardez and Tiswadi taluks is notably sparse. Available studies are primarily restricted to groundwater quality assessments based on conventional hydrochemical parameters.

Krishan et al. (2016) conducted a Water Quality Index assessment of groundwater in North Goa, including parts of the Bardez taluk, based on parameters such as pH, TDS, total hardness and chloride. While the overall water quality was found to be 'good' under pre-monsoon conditions, the study noted that groundwater in the study area occurs under unconfined conditions in sandy aquifers of the plains and semi-confined conditions in laterite and graywacke formations, with the water table generally less than 10 m from the surface. However, the study did not address saline intrusion, isotopic signatures, or seasonal groundwater–surface water interactions representing significant gaps in scientific knowledge for the area.

The Goa Groundwater Year Book (2022–23) attributed observed declines in groundwater levels to localised over-extraction, and the Goa Ground Water Policy (2015) identified stressed groundwater conditions in coastal, urban and industrial zones. However, neither document provides a hydrogeochemical or isotopic basis for delineating saline intrusion zones or understanding the mechanisms and extent of salinisation in coastal aquifers.

2.2.4 Water Stress Context: Goa as a Freshwater-Stressed Tourism Destination

Goa holds the distinction of being India's smallest state by area, yet also one of its most densely visited and rapidly urbanizing regions. The state receives approximately 8 million domestic and international tourists annually, making it a global tourist hotspot, with the coastal belt of North Goa encompassing the very taluks of Bardez and Tiswadi that are the subject of the present study hosting the highest concentration of tourism infrastructure in the country.

Per capita water availability in Goa has declined sharply, dropping from approximately 4,500 cubic metres per capita in 1980 to around 2,200 cubic metres at present. If current trends continue, Goa is projected to face chronic water stress by 2040. Sixty per cent of Goa's population lives along the urban coastal belt, and the majority of tourists flock to the shoreline, causing water demand in the coastal zone to far exceed what the natural aquifer system can sustainably supply. According to a Mongabay investigation, Goa faces a shortfall of 85 million litres of water per day. Tourism, being inherently water-intensive, exacerbates this deficit significantly, with a 2017 report by Tandem Research and The Asia Foundation establishing that 37 per cent of Goa's hotels rely on groundwater and 25 per cent purchase water from tankers that themselves largely draw from groundwater sources.

In the Bardez taluk specifically, the Assonora water treatment plant the sole treatment facility for the entire taluk has been chronically unable to meet growing demand, particularly during peak tourist seasons. Residents of Calangute, Siolim, Anjuna, Vagator and Assagao have reported severe water shortages and have organized public protests in recent years. The coastal tourism villages of Candolim, Anjuna and Benaulim have reported that over-extraction of groundwater has allowed saltwater to seep into freshwater wells and borewells. Sea-level rise and changing climate patterns are further increasing saline water intrusion into coastal aquifers, compounding an already critical situation.

Unregulated borewell drilling in high-demand areas including Panaji (in Tiswadi taluk), Calangute and Margao is rapidly depleting groundwater levels. Since the late 1990s, the coastal belt has experienced significant groundwater over-exploitation, leading to a plummeting of the water table in coastal wards. Despite the passage of the Goa Groundwater Regulation Act in 2002, this over-extraction continues largely unabated due to the absence of comprehensive monitoring and science-based management strategies.

This water stress context directly underscores the importance and urgency of the present NAQUIM 2.0 investigation. The critical dependence of Goa's resident population and its globally significant tourism sector on groundwater from coastal aquifers, combined with the documented and growing threat of saline intrusion, makes the scientific characterization and mapping of saline water ingress an imperative for sustainable water management in the region.

2.3 Identified Research Gaps and Justification for the Present Study

The review of international and national literature reveals the following critical research gaps in the context of the Bardez and Tiswadi taluks, North Goa, which the present NIH study under NAQUIM 2.0 is specifically designed to address:

a) Absence of detailed isotope-based investigations in Goa coastal aquifers: To the best of available knowledge, no published scientific study has applied stable isotope techniques ($\delta^{18}O$, $\delta^{2}H$) to characterise groundwater recharge, mixing dynamics or saline intrusion in the coastal aquifers of Bardez and Tiswadi taluks. This represents a fundamental knowledge gap for a region that is increasingly stressed by saline intrusion, tourism-driven abstraction and urbanisation.

b) No systematic mapping of lateral and vertical extent of saline intrusion: Despite anecdotal and localised evidence of saltwater ingress into coastal wells in North Goa, there is no scientifically rigorous three-dimensional delineation of the saline-freshwater interface or the lateral and vertical extent of saline influence in the aquifer systems of Bardez and Tiswadi. This prevents the formulation of spatially targeted management interventions.

c) Absence of groundwater–surface water interaction studies in the tidal estuary context: The Mandovi and Chapora rivers, which influence the study area, are tidal estuaries with complex seasonal dynamics of freshwater discharge and tidal saline penetration. No published study has investigated the isotopic or geochemical exchange between these tidal water bodies and the adjoining coastal aquifers in the study area, leaving a critical gap in understanding the role of these rivers as salinity sources.

d) Inadequate scientific basis for water management planning: The existing literature does not provide the hydro-geochemical and isotopic evidence base necessary for developing site-specific, scientifically defensible interventions such as targeted artificial recharge, abstraction regulation or safe aquifer demarcation in the coastal zones of North Goa. The present study is specifically designed to fill this gap.

e) Seasonality and climate variability not captured: Available groundwater data for the study area is largely confined to single-season assessments. The comparative pre-monsoon and post-monsoon dataset being generated by NIH covering field parameters, hydrochemistry and isotopes will for the first time enable seasonal interpretation of saline influence dynamics and groundwater quality variability in the coastal aquifer system.

In summary, the scientific literature clearly demonstrates that stable isotope investigations and hydrochemical monitoring, represent the most powerful available tool set for characterizing saline intrusion in complex coastal aquifer settings. The application of these methods to the Bardez and Tiswadi coastal aquifer system under NAQUIM 2.0 represents the first comprehensive, multidisciplinary scientific investigation of saline water ingress in this critically important and hydro-geologically underexplored region of India's west coast, and provides the foundational scientific evidence required for informed and sustainable coastal groundwater management.

3 OBJECTIVES AND SCOPE OF STUDY

The National Institute of Hydrology (NIH) aims to support the NAQUIM 2.0 coastal aquifer study in Bardez and Tiswadi taluks by undertaking stable isotope investigations to understand the processes and spatial distribution of groundwater salinity.

The objectives include collection and analysis of isotope samples from groundwater and selected surface water bodies, integration of isotope signatures with hydrochemical and groundwater level data, and mapping of saline intrusion and assessment of its status using stable isotope analysis.

The study will provide scientific inputs for identifying vulnerable aquifer zones, understanding groundwater–surface water interaction in tidal environments, and supporting development of sustainable groundwater management interventions in the coastal region.

The objectives of this study include,

1) Isotope sampling and analysis to identify saline water ingress.
2) Assessment of spatial distribution of saline water ingress

4 STUDY AREA AND DATA USED

4.1 Study area

The present study covers **Bardez and Tiswadi taluks** of North Goa district, spanning an area of about 478 sq. km along the west coast of India. The study area extends from Latitude 15° 24' 48.3192"N to 15° 42' 20.5272"N and Longitude 73° 43' 54.4182"E to 73° 58' 44.745" E. The study area encompasses 45 villages of Bardez and 39 villages of Tiswadi Taluks.

The region is characterized by laterite-capped plateaus, coastal alluvium and underlying schistose formations, forming predominantly shallow phreatic aquifers that experience significant seasonal fluctuations in groundwater levels. The hydrogeological system is strongly influenced by high monsoonal rainfall, intensive groundwater abstraction, rapid post-monsoon depletion, and hydraulic connectivity with tidal rivers such as the Mandovi and Chapora, making the coastal aquifers vulnerable to saline ingress.

In such complex coastal settings, conventional hydrochemical indicators alone are often insufficient to conclusively identify the origin and processes of groundwater salinization. Therefore, stable isotope investigations become critical for distinguishing between seawater intrusion, tidal river influence, evaporation effects and local recharge contributions.

Isotope signatures provide valuable insights into groundwater recharge mechanisms, mixing dynamics and groundwater–surface water interactions, enabling scientific mapping of saline intrusion and assessment of its status within the aquifer system. This understanding is essential for developing site-specific groundwater management strategies under NAQUIM 2.0 aimed at ensuring long-term sustainability of coastal groundwater resources.

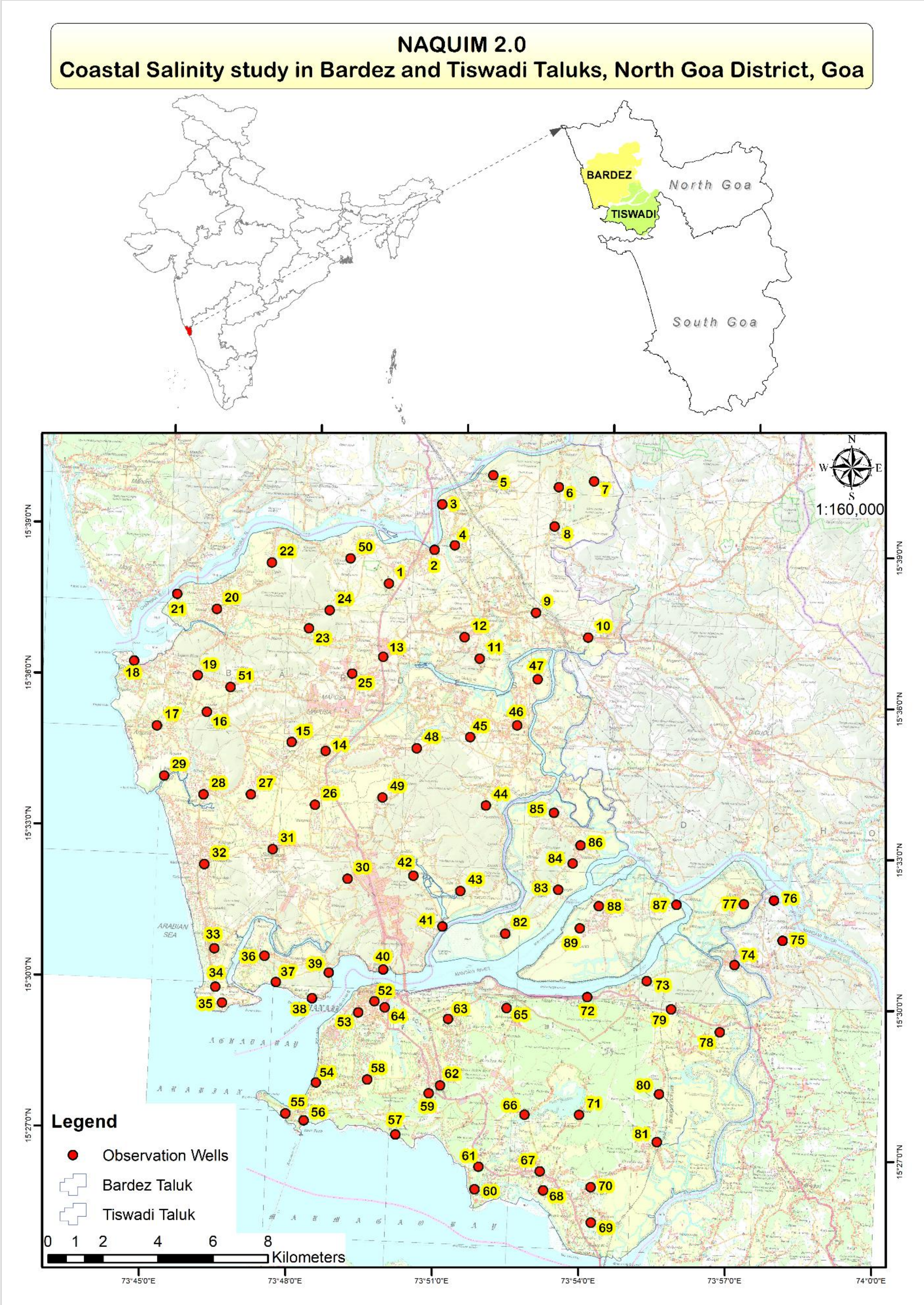


Figure 1: Index map of the study area

4.2 Data products used in the study

The study was taken up with extensive field sampling with the base maps prepared from Survey of India Toposheets, thematic layers such as Geology, Aquifers map, Landuse-Landcover and other necessary information from published sources.

The key observation wells were selected in the field based on grid size of 5Km x 5Km for identifying each well. A total of 89 wells were shortlisted for sampling during the study period.

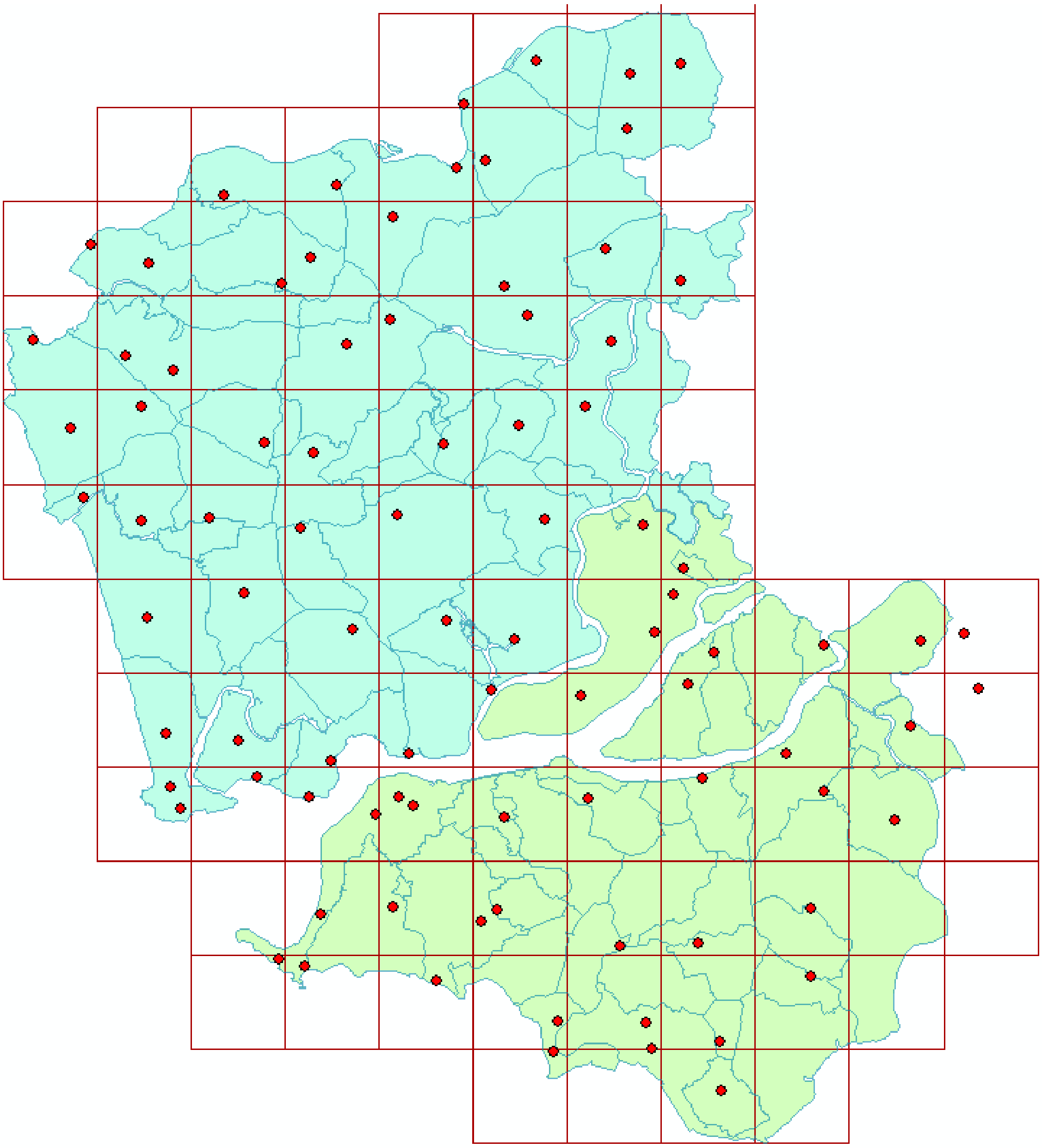


Figure 2: 5Km x 5Km Grids for the study area

5 METHODOLOGY

The methodology adopted by NIH for the coastal aquifer salinity study in Bardez and Tiswadi taluks follows an integrated, multi-phase approach that encompasses pre-field planning with CGWB study team, base map preparation, systematic key well identification with CGWB study team and sampling network design, comprehensive field data collection including in-situ water quality measurements, collection of groundwater and surface water samples for stable isotope analysis, and subsequent laboratory processing and scientific interpretation. The overall methodological framework is presented in Figure 3 and described in detail in the following sections.

5.1 Pre-Field Planning and Base Map Preparation

Prior to the commencement of field investigations, a comprehensive review of available secondary information was carried out to establish the scientific and spatial framework for the study. Base maps for the study area covering Bardez and Tiswadi taluks (total area 478 sq. km) were prepared using Survey of India (SOI) topographic sheets at appropriate scales. Relevant thematic layers were collated, georeferenced and integrated into a GIS environment, including:

1) Geological map of the study area, depicting lateritic, alluvial, and schistose formations relevant to aquifer characterization.
2) Aquifer disposition and hydrogeological maps, indicating the spatial distribution and extent of phreatic and semi-confined aquifer systems.
3) Land use and land cover (LULC) map, prepared from published sources and remote sensing data, to understand anthropogenic pressures including urbanization, tourism infrastructure and coastal development.
4) Drainage network and hydrological features, including the courses of the Mandovi and Chapora rivers, their tidal reaches, estuaries, backwaters and influencing water bodies.
5) Administrative and infrastructure maps indicating population centers, tourist zones, industrial areas and groundwater extraction hotspots.

The pre-field collation of thematic information enabled identification of potential sampling zones, hydro-geologically significant locations, and areas of likely saline influence prior to field mobilization, thereby optimizing field effort and ensuring scientific coverage across the full spatial extent of the study area.

5.2 Identification of Key Wells and Design of Sampling Network

5.2.1 Grid-Based Well Selection Approach

The sampling network for groundwater monitoring and isotope collection was designed on the basis of a systematic spatial grid of 5 km × 5 km overlaid on the study area. This grid-based approach ensures uniform spatial coverage across the study area, prevents clustering of sampling points and facilitates statistically representative interpretation of hydrochemical and isotopic data across the full spatial extent of the coastal aquifer system. The grid design also allows for the construction of lateral salinity profiles and enables comparison of isotopic signatures across the coastal-inland gradient from the shoreline and tidal river zones towards the inland recharge areas.

Within each grid cell, field reconnaissance was carried out to identify the most representative and accessible observation well, with preference given to open dug wells that penetrate the shallow phreatic lateritic aquifer, as these are the primary aquifer type in the study area and are most susceptible to saline water ingress. Where available, borewells penetrating deeper semi-confined formations were also included to enable assessment of the vertical extent of saline influence.

5.2.2 Criteria for Key Well Selection

Wells were selected for inclusion in the sampling network based on the following criteria:

i) Location within an identified 5 km × 5 km grid cell, ensuring spatial representativeness.
ii) Accessibility and availability of the well owner's cooperation for repeated seasonal sampling.
iii) Hydrological significance, including proximity to tidal rivers, coastal shoreline, saline ingress risk zones, and known areas of groundwater quality concerns.
iv) Well type and construction details, including depth, casing, and aquifer tapped, to enable depth-stratified interpretation of isotopic data.
v) Absence of recent chemical dosing or treatment that could compromise isotopic and hydrochemical data integrity.

Following extensive field reconnaissance across the study area, a total of 89 key observation wells were shortlisted and finalized for sampling during the study period, comprising predominantly open dug wells and one shallow borewell distributed across the coastal and inland zones of Bardez and Tiswadi taluks. The spatial distribution of selected wells is presented in Figure 1.

5.2.3 Surface Water and Additional Sampling Locations

In addition to the 89 groundwater wells, surface water sampling was carried out at selected locations in rivers, estuaries, tidal channels and other hydraulically influencing water bodies in and around the study area. These include representative sites on the Mandovi and Chapora rivers, their tidal tributaries and backwater systems. Surface water samples provide essential end-member data for isotopic mixing calculations and enable characterization of the hydraulic connectivity between surface water and groundwater systems, a critical input for understanding the role of tidal rivers as vectors of saline water introduction into coastal aquifers.

Seawater samples were also collected at representative coastal locations to establish the isotopic and hydrochemical signature of the marine end-member, which is required for quantitative mixing analysis between fresh groundwater and seawater components.

5.3 Field Sampling Programme

5.3.1 Seasonal Sampling Strategy

A two-season comprehensive field sampling programme was carried out by NIH teams to capture the full seasonal variability of groundwater quality and isotopic signatures in the coastal aquifer system. Sampling was conducted during both the pre-monsoon and post-monsoon periods, as follows:

i) Pre-monsoon sampling: Carried out during the driest period of the year (typically March–May), when groundwater levels are at their annual minimum, abstraction stress is at its peak, and the risk of saline water encroachment is highest. Pre-monsoon isotopic and hydrochemical data represent the most critical period for assessing the extent and status of saline intrusion.

ii) Post-monsoon sampling: Carried out following the southwest monsoon season (typically October–November), when groundwater levels are replenished and the aquifer system reflects the influence of fresh monsoon recharge. Post-monsoon data provide the comparative baseline to assess seasonal recovery, freshening trends and the persistence of saline signatures in the aquifer.

The two-season dataset together enables analysis of the temporal dynamics of saline ingress a critical dimension of coastal aquifer management that single-season studies are unable to address and supports the assessment of whether saline influence is seasonal and reversible or indicative of progressive, long-term intrusion.

5.3.2 In-Situ Water Quality Measurements

At each well location, comprehensive in-situ measurements of critical water quality and hydrogeological parameters were recorded at the time of sampling using calibrated portable field instruments. On-site measurements were prioritized to capture parameters that are sensitive to atmospheric exposure and temperature change, and which would not be reliably preserved through sample storage and laboratory transport. The parameters measured in the field at each location are listed in Table 1.

Table 1: In-situ parameters measured during field sampling and their relevance to coastal salinity assessment

Parameter	Unit / Instrument	Significance in Coastal Salinity Studies
Electrical Conductivity (EC)	µS/cm portable EC meter	Primary indicator of total dissolved ions; proxy for salinity and saline ingress
Total Dissolved Solids (TDS)	mg/L TDS meter	Indicates dissolved mineral load; correlates with EC for salinity assessment
Salinity	ppt/PSU portable salinity probe	Direct measure of salt concentration; identifies saline-influenced wells
pH	pH units portable pH meter	Reflects water–rock interaction and carbonate equilibrium; supports hydrochemical interpretation
Dissolved Oxygen (DO)	mg/L DO meter	Indicates redox environment; relevant for iron and manganese mobilization in lateritic aquifers
Oxidation Reduction Potential (ORP)	mV ORP electrode	Characterizes redox conditions; supports interpretation of geochemical reactions in mixing zones
Temperature	°C thermometer / multi-parameter probe	Required for correction of EC and pH readings; supports isotope–temperature relationship analysis
Depth to Static Groundwater Level (DTWL)	m bgl steel tape / electronic dipper	Indicates seasonal water table dynamics; provides hydraulic gradient information for flow direction and saline ingress risk assessment

All field instruments were calibrated prior to each sampling campaign using standard solutions, and calibration records were maintained. GPS coordinates (latitude, longitude and altitude) of each sampling location were recorded using a handheld GPS device, and details of the well including well type, depth, casing, aquifer tapped, land use in the vicinity and any observed signs of saline influence were recorded in standardized field datasheets.

5.3.3 Groundwater Sample Collection for Stable Isotope Analysis

Groundwater samples for stable isotope analysis ($\delta^{18}O$ and $\delta^{2}H$) were collected from all 89 key observation wells during both the pre-monsoon and post-monsoon sampling campaigns. Samples were collected following purging of the well to ensure representative formation water was obtained, where operationally feasible. The collection protocol was as follows:

a) Wells were purged using the existing mechanism or manually by bailer until field parameters (EC, pH, and temperature) stabilized, indicating representative aquifer water.

b) Samples were collected in polypropylene (PP) bottles of 30mL capacity, pre-cleaned and dried.

c) Bottles were rinsed three times with the sample water before final collection to eliminate any residual contamination.
d) Sample bottles were completely filled without headspace and sealed immediately with airtight caps and parafilm to prevent evaporative fractionation, which would alter the isotopic composition.
e) Sample bottles were labelled with unique sample codes cross-referenced to field data sheets, GPS coordinates, and date and time of collection.
f) Samples were stored in cool, dark conditions during field transport and dispatched to the NIH isotope laboratory at Roorkee at the earliest opportunity after field sampling.

A total of 89 groundwater samples per season covering pre-monsoon and post-monsoon periods along with surface water samples from rivers, tidal reaches and coastal water bodies were collected and dispatched for isotope analysis, resulting in a comprehensive spatial and temporal isotopic dataset for the study area.

5.3.4 Surface Water Sample Collection

Surface water samples were collected from representative locations in the Mandovi river, Chapora river, their tidal tributaries, estuaries, backwater channels and other hydraulically connected water bodies within the study area. Sampling sites were selected to capture the full range of salinity conditions from fresh upstream reaches to tidal and brackish zones near the coast. The same field measurement and sample collection protocols as applied for groundwater were followed for surface water, with additional observations of tidal conditions and flow direction recorded at the time of sampling.

5.4 Stable Isotope Analysis at NIH Isotope Laboratory, Roorkee

5.4.1 Analytical Facility

All groundwater and surface water samples collected during the field campaigns were dispatched to the Isotope Hydrology Laboratory of the National Institute of Hydrology, Roorkee (Uttarakhand), which is the nodal isotope laboratory of NIH. The laboratory is equipped with state-of-the-art instrumentation for the analysis of stable water isotopes and is accredited for environmental isotope studies in support of national hydrological investigations. The NIH Roorkee isotope laboratory has extensive experience in isotope-based groundwater studies across diverse hydrogeological settings in India, including coastal aquifer investigations.

5.4.2 Parameters Analyzed

The following stable isotope parameters were analyzed for all water samples:

i) Stable oxygen isotope ratio ($\delta^{18}O$): The ratio of less abundant to abundant isotopes of oxygen ($^{18}O/^{16}O$) expressed in per mil (‰) relative to the Vienna Standard Mean Ocean Water (V-SMOW) standard. $\delta^{18}O$ is a primary tracer for identifying the origin of water, degree of evaporation, and mixing between freshwater and seawater components.

ii) Stable hydrogen isotope ratio (δ^2H): The ratio of less abundant to abundant isotopes of hydrogen ($^2H/^1H$), expressed in per mil (‰) relative to V-SMOW. δ^2H is used in conjunction with $\delta^{18}O$ to plot samples on the Global Meteoric Water Line (GMWL: $\delta^2H = 8\delta^{18}O + 10$) and the Local Meteoric Water Line (LMWL) to identify meteoric recharge, evaporative enrichment and marine mixing signatures.

5.4.3 Analytical Method

Stable isotope ratios ($\delta^{18}O$ and δ^2H) were determined using Isotope ratio mass spectrometer (IRMS) connected with water equilibration system supplied by Elementar. All results are reported relative to the V-SMOW standard and using delta (δ) notation (Craig et al., 1961). The stable isotope ratios and D-excess are expressed in per mille (‰). The instrument provides isotopic measurements with analytical precision within ±0.12‰ for $\delta^{18}O$ and ±1.0‰ for δ^2H. Internal laboratory standards and reference materials were run alongside field samples for quality assurance and analytical calibration. Deuterium excess (D-excess or d) is a second-order stable isotope parameter defined as, $d= \delta^2 H-8 \times \delta^{18}O$ (Dansgaard, 1964).

5.5 Data Interpretation and Analysis Framework

The interpretation of field data and isotope analytical results is carried out through a structured, multi-method framework designed to address the specific scientific objectives of NIH under the NAQUIM 2.0 study. The key elements of the interpretation framework are described below.

5.5.1 Hydrochemical Data Processing and Seasonal Comparison

In-situ field parameter data (EC, TDS, salinity, pH, DO, ORP, temperature and DTWL) from pre-monsoon and post-monsoon sampling campaigns are compiled, quality-checked and subjected to statistical analysis. Spatial distribution maps of key parameters are generated using GIS interpolation techniques (IDW / kriging) to identify zones of elevated salinity, depressed water levels and anomalous water quality conditions. Seasonal comparisons between pre-monsoon and post-monsoon datasets are used to assess the temporal variability of saline influence and groundwater quality across the study area.

5.5.2 Isotope Data Interpretation

Stable isotope data are interpreted using the following analytical approaches:

(i) $\delta^{18}O$ vs. δ^2H bivariate plot: All groundwater and surface water samples are plotted against the Global Meteoric Water Line (GMWL) and the Local Meteoric Water Line (LMWL) for the Goa–West Coast region. Deviations from the GMWL are interpreted as evidence of evaporative enrichment, marine influence or mixing with non-meteoric water sources. Samples plotting on or near the GMWL indicate fresh meteoric recharge, while samples deviating towards the seawater end-member indicate varying degrees of saline mixing.

(ii) End-member mixing analysis: Isotopic signatures of established end-members fresh meteoric groundwater, local rainfall, river water, tidal/estuarine water and seawater are used to quantify the fractional contribution of each component to sampled groundwater using binary and ternary mixing models. This approach directly enables assessment of the degree of saline intrusion at each sampling location.

(iii) Isotope–hydrochemistry correlation: Isotopic data are correlated with in-situ field parameters (particularly EC, TDS and salinity) and seasonal DTWL data to identify hydrogeological controls on saline ingress and to validate isotope-based interpretations with field evidence.

(iv) Spatial mapping of isotopic signatures: $\delta^{18}O$ and $\delta^{2}H$ values are spatially interpolated and mapped to delineate zones of isotopically enriched (saline-influenced) and depleted (fresh recharge-dominated) groundwater, enabling visual representation of the lateral extent of saline intrusion across the study area.

(v) Depth-profile analysis: Where samples from different depth aquifers are available at the same or nearby locations, isotopic profiles are used to assess the vertical distribution of saline influence, contributing to understanding of the vertical extent of saline intrusion in the coastal aquifer system.

5.5.3 Mapping of Saline Intrusion Status

The combined outputs of hydrochemical spatial analysis and isotopic mapping are integrated to prepare thematic maps delineating the status and extent of saline intrusion in the Bardez and Tiswadi coastal aquifer system. These maps include:

i) Spatial distribution map of EC / TDS / salinity (pre-monsoon and post-monsoon).

ii) Depth to water level maps showing seasonal groundwater table dynamics.

iii) $\delta^{18}O$ and $\delta^{2}H$ distribution maps indicating isotopic enrichment zones.

iv) Saline intrusion zonation map identifying fresh, transitional (mixing) and saline-dominated groundwater zones based on integrated isotopic and hydrochemical evidence.

v) Groundwater–surface water interaction zones based on isotopic end-member analysis.

5.5.4 Integration with CGWB Data for Aquifer Management Inputs

The isotope-based results generated by NIH are integrated with the broader NAQUIM 2.0 dataset being compiled by CGWB including aquifer disposition maps, groundwater level data from 95 key wells, hydrogeological information and existing quality data to provide a comprehensive scientific basis for the preparation of the aquifer management plan. Specific management inputs from NIH include identification of vulnerable aquifer zones susceptible to saline intrusion, delineation of safe aquifer pockets suitable for drinking water supply, and scientific guidance for the design of artificial recharge, abstraction regulation and saline ingress containment interventions.

5.6 Summary of Methodological Framework

The complete methodological workflow adopted by NIH for the present study is summarized in Figure 3 below. The workflow progresses from pre-field planning and data collation, through systematic field sampling and in-situ measurements, to laboratory isotope analysis and integrated data interpretation, culminating in the generation of scientific outputs for saline intrusion mapping and groundwater management planning under NAQUIM 2.0.

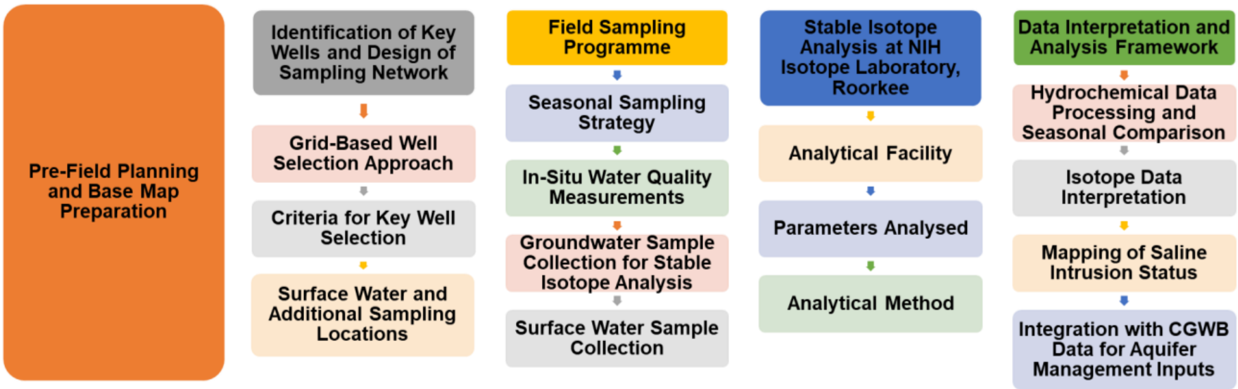


Figure 3: NIH Methodological framework flowchart for coastal aquifer salinity study, Bardez & Tiswadi, North Goa

6 RESULTS AND DISCUSSION

This chapter presents the results of the comprehensive field investigations and stable isotope analysis carried out by NIH in Bardez and Tiswadi taluks, North Goa, under NAQUIM 2.0 (AAP 2024–25). The measured data of physico-chemical parameters and stable isotopes from 89 key observation wells sampled across Bardez and Tiswadi taluks during pre-monsoon (PRM) and post-monsoon (POM) seasons form the basis of the analysis.

The results are organized and discussed under in-situ hydrochemical parameters, stable isotope parameters, spatial distribution patterns interpreted through IDW-interpolated GIS maps, identification of wells affected by and vulnerable to saline water intrusion, and an integrated assessment of the status of coastal aquifer salinization. All discussions are aligned with the scientific objectives of NIH under NAQUIM 2.0.

6.1 Overview of the Dataset

A total of 89 groundwater wells were sampled across the study area during both seasons. The dataset encompasses in-situ measurements of eight field parameters Depth to Water Level (DTWL), Electrical Conductivity (EC), Total Dissolved Solids (TDS), Salinity, pH, Dissolved Oxygen (DO), Temperature and

Oxidation-Reduction Potential (ORP). Further, additional sampling for stable isotope analysis ($\delta^{18}O$, $\delta^{2}H$) and derived Deuterium Excess (D-excess) values. Pre-monsoon samples were collected during the period of maximum groundwater stress and minimum water table, while post-monsoon samples reflect the state of the aquifer following monsoon recharge. Summary statistics for all parameters across both seasons are presented in Table 2.

Table 2: Summary Statistics of Hydrochemical and Isotope Parameters.

Parameter	PRM Min	PRM Max	PRM Mean	PRM Median	POM Min	POM Max	POM Mean	POM Median
DTWL (m bgl)	1.28	19.00	5.00	4.08	0.40	18.04	3.95	3.45
TDS (mg/L)	11.65	1477	140.0	70.0	10.76	541	81.6	54.5
EC (µS/cm)	25	2890	277.2	144.8	25.2	1096	171.5	115.5
Salinity (ppt)	0.010	1.500	0.134	0.070	0.010	0.540	0.081	0.050
pH	4.78	8.00	6.05	6.07	4.58	7.13	5.67	5.60
DO (mg/L)	0.95	11.3	3.95	3.61	1.60	11.32	3.83	3.78
$\delta^{18}O$ (‰)	−2.543	+0.777	−1.612	−1.748	−4.139	−1.517	−2.240	−2.212
$\delta^{2}H$ (‰)	−8.984	+7.309	−4.054	−4.390	−22.259	−0.141	−7.573	−7.302
D-excess (‰)	−2.534	12.210	8.844	9.107	4.203	17.246	10.344	10.381

6.2 Hydrochemical Parameters

In-situ field parameter data (EC, TDS, salinity, pH, DO, ORP, temperature and DTWL) from pre-monsoon and post-monsoon sampling wells are analyzed with reference to the study area and the following inferences are drawn from the analysis results as plotted in Figure 10,

Depth to Water Table (DTWL)

The depth to static water level was measured at 89 wells during both seasons. Pre-monsoon DTWL ranged from 1.28 m to 19.00 m below ground level (bgl), with a mean of 5.00 m and median of 4.08 m bgl. Post-monsoon DTWL ranged from 0.40 m to 18.04 m bgl, with a mean of 3.95 m and median of 3.45 m bgl. The mean seasonal decline in water table between POM and PRM is approximately 1.05 m, indicating monsoon recharge contribution to the phreatic lateritic aquifer system (refer Table 2, DTWL Prm mean – Pom mean).

The shallow water table depth with a majority of wells having DTWL less than 5 m bgl in both seasons is characteristic of the unconfined lateritic aquifers of North Goa. Such shallow water tables in proximity to the coastline and tidal rivers significantly increase the susceptibility of these aquifers to saline water ingress, as even minor disruptions to the freshwater head can result in landward movement of the freshwater-saltwater interface. The maximum pre-monsoon DTWL of 19.00 m corresponds to wells located on higher lateritic plateaus, where the saturated zone is deeper and relatively protected from direct saline influence.

The IDW interpolation map of DTWL (Figure 4) illustrates the spatial distribution of water table depths across the study area. The coastal and low-lying zones of Bardez particularly in the Calangute, Candolim and Siolim areas and the Tiswadi coastal fringe show the shallowest water tables during both seasons, which are also the zones of highest saline intrusion risk. The deeper water tables are confined to the inland plateau areas in eastern Bardez. The seasonal water table recovery map highlights zones of good recharge response (inland) versus zones of limited recovery (coastal), which are likely constrained by saline water occupying the capillary fringe.

Mean depth dropped from 5.00 m (pre-monsoon: PRM) to 3.95 m (post-monsoon: POM), confirming monsoon recharge to shallow lateritic aquifers. Seasonal fluctuation of ~1 m is consistent with thin phreatic aquifer behavior typical of Goa's laterite terrain.

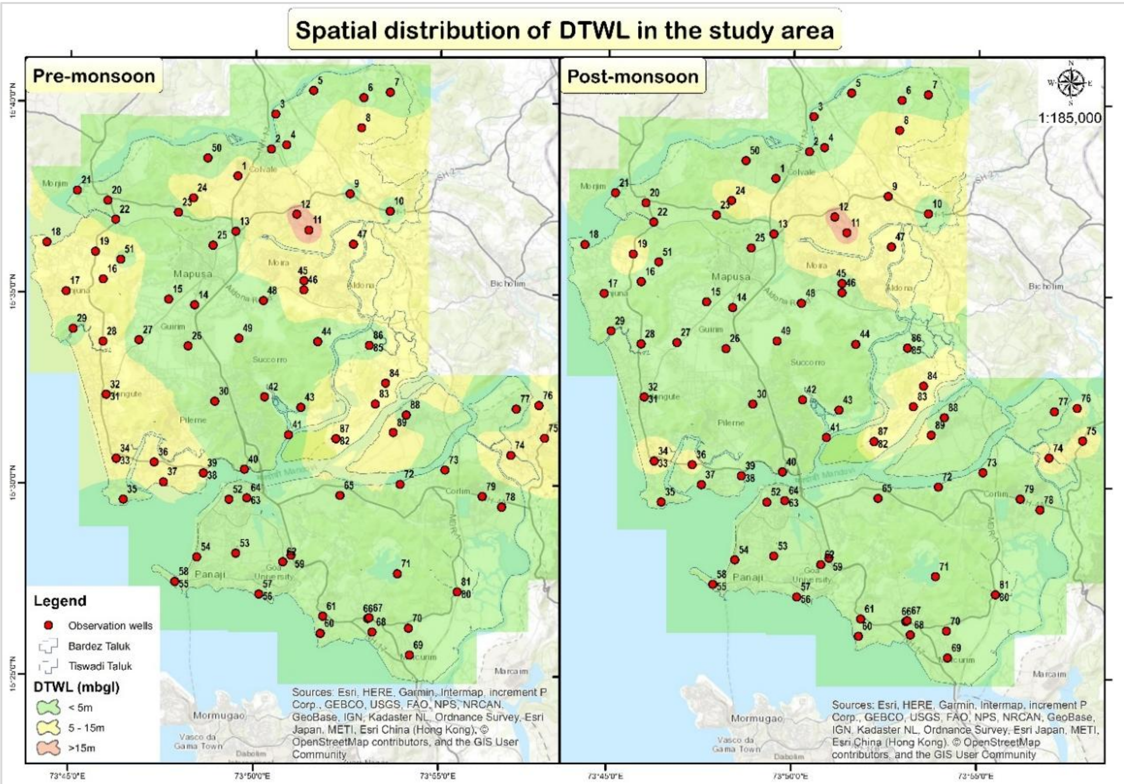


Figure 4: DTWL Map of Pre-Monsoon and Post-Monsoon

Electrical conductivity (EC)

Electrical conductivity (EC) is the most sensitive field indicator of total dissolved ionic concentration and is the primary proxy parameter for identifying saline groundwater in coastal studies. Pre-monsoon EC values ranged from 25 to 2,890 µS/cm, with a mean of 277.2 µS/cm and median of 144.8 µS/cm. Post-monsoon EC ranged from 25.2 to 1,096 µS/cm, with a mean of 171.5 µS/cm and median of 115.5 µS/cm (Table 2, Figure 5).

The maximum pre-monsoon EC of 2,890 µS/cm is nearly four times the BIS drinking water standard of 750 µS/cm which confirms the presence of highly saline groundwater in a subset of coastal wells. Significantly, even the post-monsoon maximum of 1,096 µS/cm exceeds the potable threshold, indicating that saline conditions in the most affected wells are not fully reversed by monsoon recharge, pointing to persistent or progressive saline intrusion rather than a merely seasonal phenomenon.

The frequency analysis of EC values reveals that approximately 12–15% of wells exceed 750 µS/cm in the pre-monsoon season and approximately 6–8% continue to exceed this threshold post-monsoon. Wells with EC between 400–750 µS/cm which belongs to the intermediate brackish range represent a further 15–18% of the sampled wells during the pre-monsoon season, indicating a large zone of transitional, saline-influenced groundwater extending beyond the most severely affected coastal locations.

The IDW map of EC distribution (Figure 5) clearly delineates a high-EC coastal zone in western Bardez and the southern coastal fringe of Tiswadi, broadly corresponding to the zones of lowest DTWL and greatest proximity to tidal water bodies. The spatial pattern confirms the lateral extent of saline influence and provides a basis for delineating primary and secondary saline intrusion zones.

PRM mean of 277 µS/cm declined to 171 µS/cm (POM). The PRM max of 2,890 µS/cm (nearly 4× the potable limit of 750 µS/cm) is a strong indicator of seawater mixing in select wells, particularly in proximity to the Mandovi estuary.

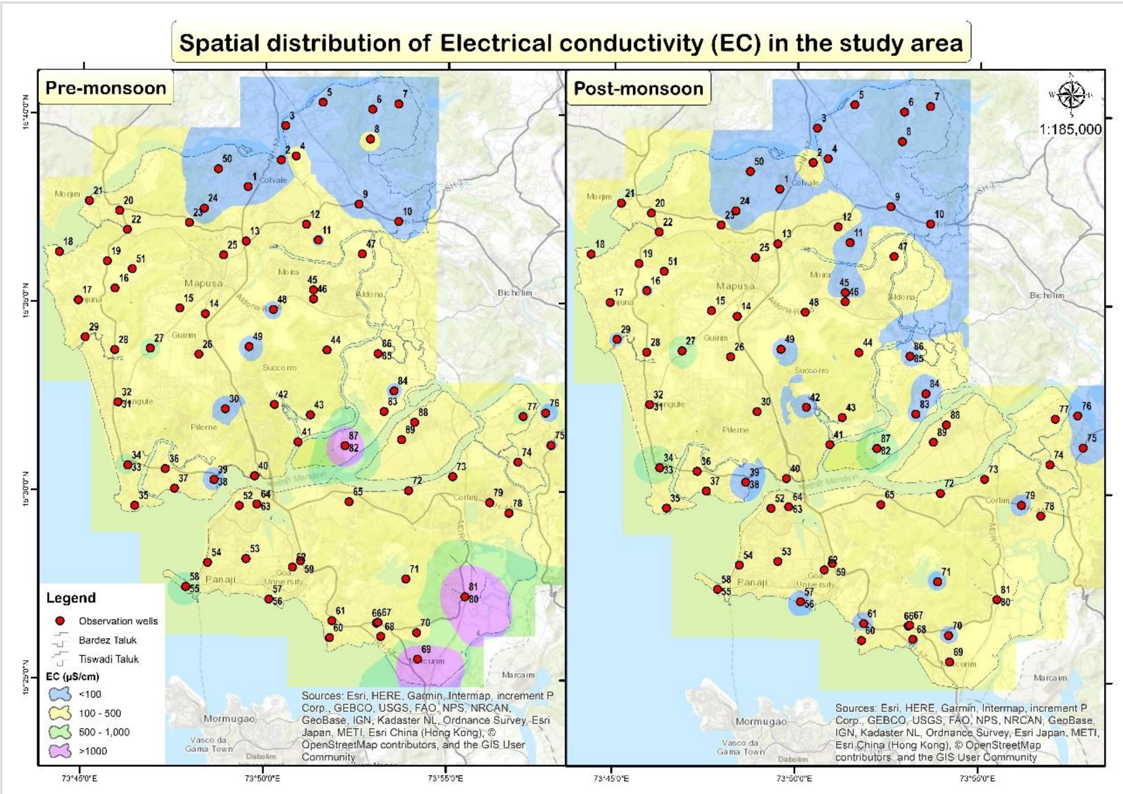


Figure 5: EC distribution map of Pre-Monsoon and Post-Monsoon seasons

Total Dissolved Solids (TDS)

TDS values closely mirror the EC trend, as expected, given that both parameters reflect total ionic load. Pre-monsoon TDS ranged from 11.65 to 1,477 mg/L (mean 140.0 mg/L; median 70.0 mg/L), while post-monsoon TDS ranged from 10.76 to 541 mg/L (mean 81.6 mg/L; median 54.5 mg/L). The near-halving of mean TDS between the pre-monsoon and post-monsoon seasons is a strong indicator of freshwater dilution by monsoon recharge across the majority of the sampled well network.

However, the pre-monsoon maximum TDS of 1,477 mg/L is nearly three times the BIS acceptable limit of 500 mg/L and approaching the permissible limit of 2,000 mg/L which in the most saline wells is highly significant. Post-monsoon persistence of TDS above 500 mg/L in several coastal wells confirms that the saline ion mass in aquifer storage is not fully flushed by a single monsoon season. This has direct implications for the NAQUIM 2.0 management plan, specifically for the design of artificial recharge structures aimed at augmenting the freshwater head in coastal areas to counteract saline ingress.

Mean nearly halved from 140 mg/L (PRM) to 82 mg/L (POM), showing dilution by fresh monsoon recharge. However, PRM max of 1,477 mg/L is well above the BIS limit of 500 mg/L which flags high-saline wells near the coast and tidal rivers.

Salinity

PRM mean 0.134 ppt, POM 0.081 ppt. The PRM maximum of 1.5 ppt confirms brackish to saline groundwater in some of the coastal wells, which partially recovers post-monsoon but does not fully freshen, suggesting persistent saline intrusion.

Groundwater salinity ranged from 0.010 to 1.500 ppt during the pre-monsoon season (mean 0.134 ppt; median 0.070 ppt) and from 0.010 to 0.540 ppt post-monsoon (mean 0.081 ppt; median 0.050 ppt). Freshwater is defined as salinity below 0.5 ppt (500 mg/L total salt); brackish water falls between 0.5 and 30 ppt. The pre-monsoon maximum of 1.500 ppt firmly classifies the most affected wells as brackish, approaching the lower range of sea-affected coastal groundwater. Even post-monsoon, the maximum of 0.540 ppt marginally exceeds the freshwater threshold in at least one well, confirming persistent saline conditions at the most vulnerable locations.

Salinity above 0.5 ppt was recorded in approximately 5–7% of wells during the pre-monsoon season. An additional 10–12% of wells showed salinity in the 0.2–0.5 ppt range, representing a zone of moderate brackish influence. The spatial distribution of salinity broadly aligns with EC and TDS patterns, reinforcing the integrity of the dataset and the consistency of field measurements.

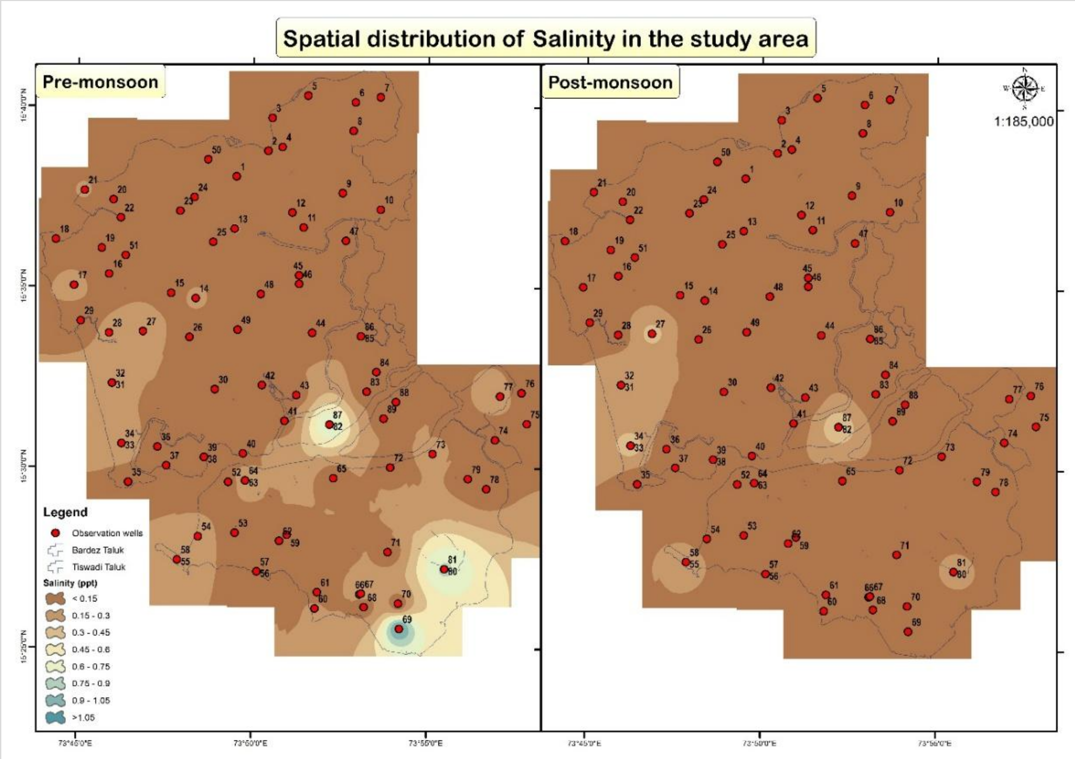


Figure 6: Salinity distribution in the study area

pH

Groundwater pH in the study area is consistently mildly acidic, with pre-monsoon values ranging from 4.78 to 8.00 (mean 6.05; median 6.07) and post-monsoon values from 4.58 to 7.13 (mean 5.67; median 5.60). The acidic character of the majority of wells is consistent with the hydrogeological setting of lateritic terrain, in which percolating rainwater acquires acidity through interaction with minerals in the weathered zone.

The slight reduction in mean pH from pre-monsoon (6.05) to post-monsoon (5.67) reflects increased infiltration of monsoon rainfall in which in the coastal Goa region is characterized by moderate acidity due to dissolved CO_2 causing diluting and acidifying the groundwater. A few wells with pH below 5.0 in both seasons are located in zones of potentially high organic matter content or proximity to anthropogenic contamination sources in the urbanized coastal belt.

Conversely, the maximum pre-monsoon pH of 8.00 in one well likely reflects carbonate-buffered conditions in a deeper or semi-confined aquifer, or influence from alkaline marine sediments in the coastal zone. Alkaline pH in coastal wells can be an indicator of saline water mixing, as seawater has a characteristic pH of approximately 8.1–8.3.

Slightly acidic throughout (PRM mean 6.05, POM 5.67), consistent with lateritic terrain which imparts acidity. Post-monsoon decline in pH reflects increased infiltration of acidic monsoon water through organic-rich laterite soils.

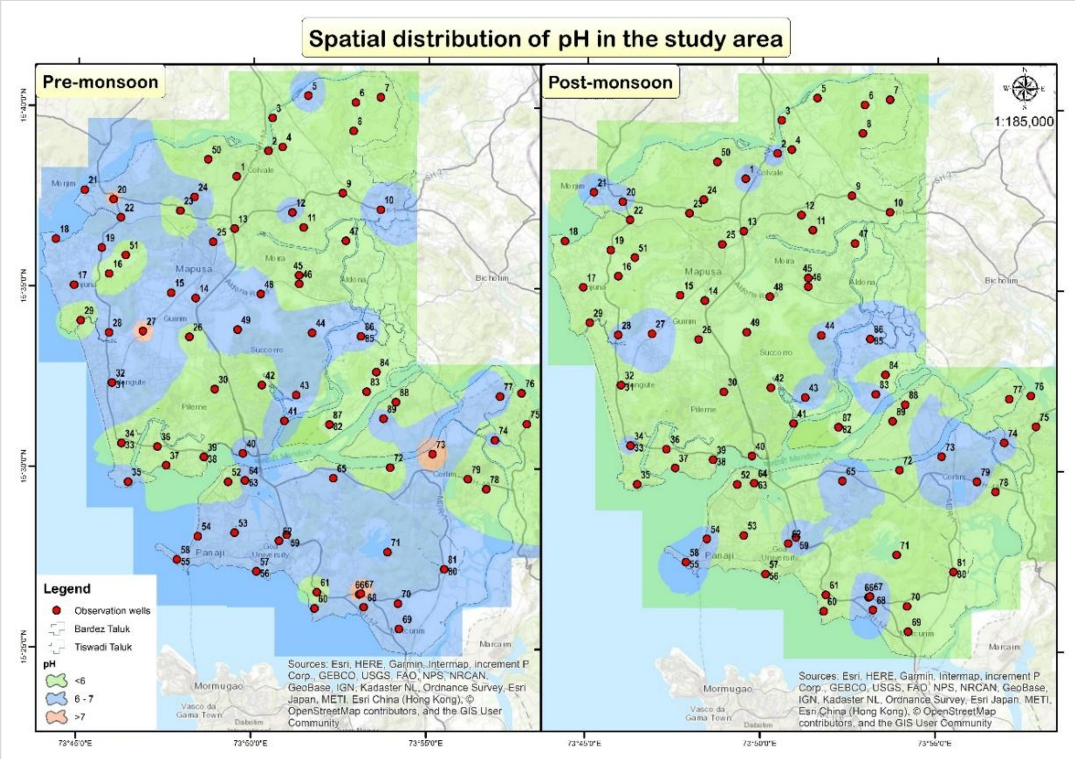


Figure 7: pH distribution map in the study area

Dissolved Oxygen (DO)

Dissolved oxygen in the pre-monsoon season ranged from 0.95 to 11.3 mg/L (mean 3.95 mg/L; median 3.61 mg/L) and from 1.60 to 11.32 mg/L post-monsoon (mean 3.83 mg/L; median 3.78 mg/L). The majority of wells fall below the standard threshold of 5.0 mg/L in both seasons, indicating mildly reducing to sub-oxic conditions in the shallow phreatic lateritic aquifer which is a common characteristic of shallow dug wells in tropical coastal settings where organic matter decomposition exerts significant oxygen demand. The pre-monsoon DO range is more consistently in the 1–10 mg/L range, with higher values in wells with good hydraulic connectivity to the land surface and active recharge.

Post-monsoon DO values are broadly similar to pre-monsoon medians, reflecting a balance between increased recharge-driven oxygenation and continued biological oxygen demand in the saturated zone. The spatial distribution of DO (refer Figure 8) in some of the wells is expected to show lower values in stagnant coastal wells with saline influence, where sulphate reduction and other anaerobic biogeochemical processes can significantly deplete dissolved oxygen.

Mean values of 3.95 mg/L (PRM) and 3.8 mg/L (POM), both below the 5 mg/L aquatic standard which indicate mildly reducing conditions in many wells.

Temperature

Groundwater temperature ranged from 25.8 to 33.5°C across all wells with a mean of 29.2 ± 1.2°C, confirming that the aquifer thermal regime is consistent with the regional warm tropical climate of the North Goa coastal zone. Post-monsoon groundwater temperatures were marginally lower than pre-monsoon, reflecting the cooling effect of cooler monsoon rainfall infiltration recharging the shallow phreatic aquifer.

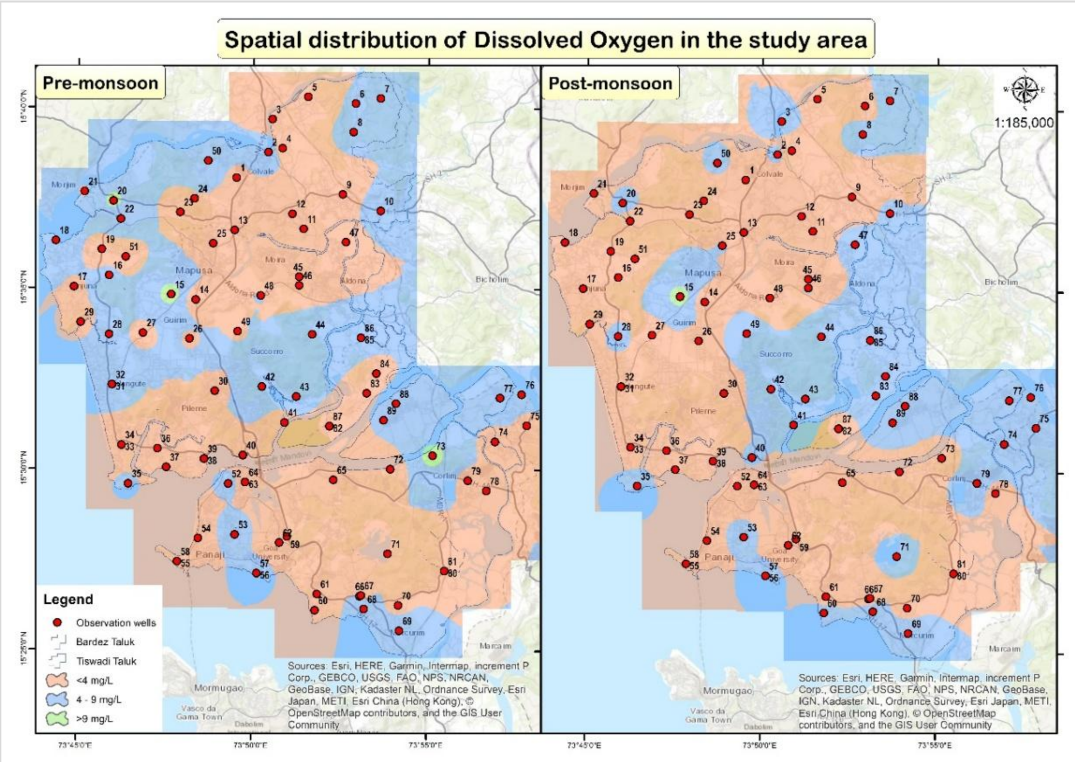


Figure 8: Dissolved Oxygen distribution in the study area

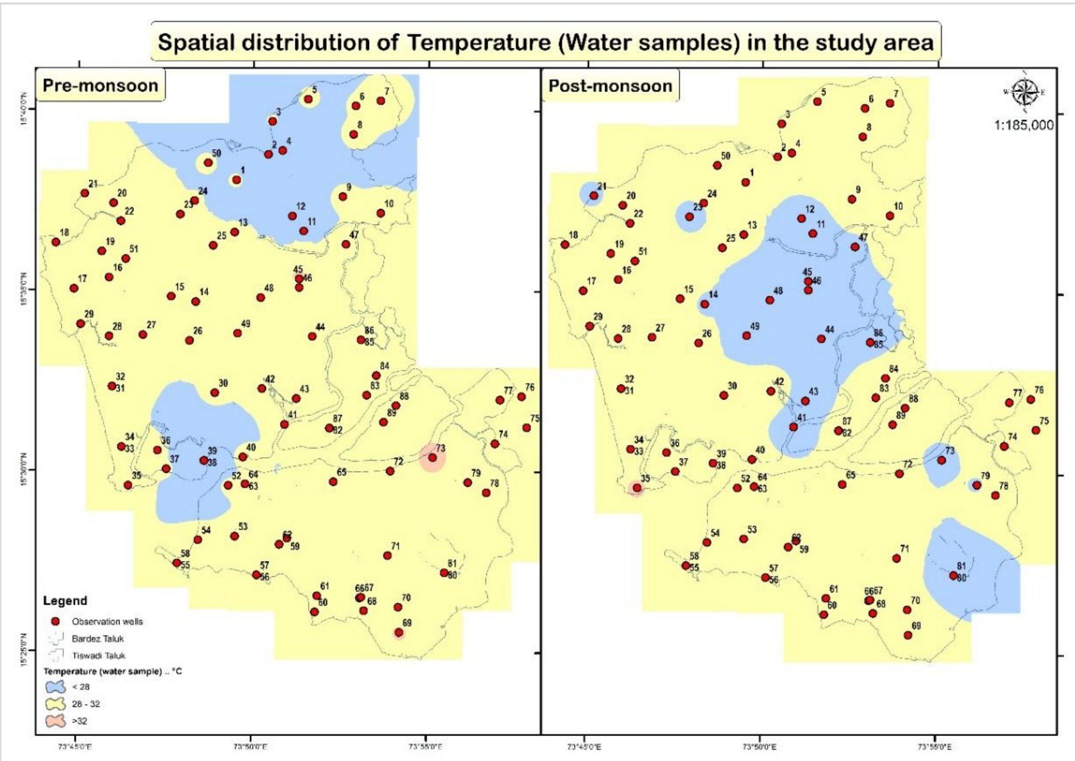


Figure 9: Temperature of water samples in the observation wells.

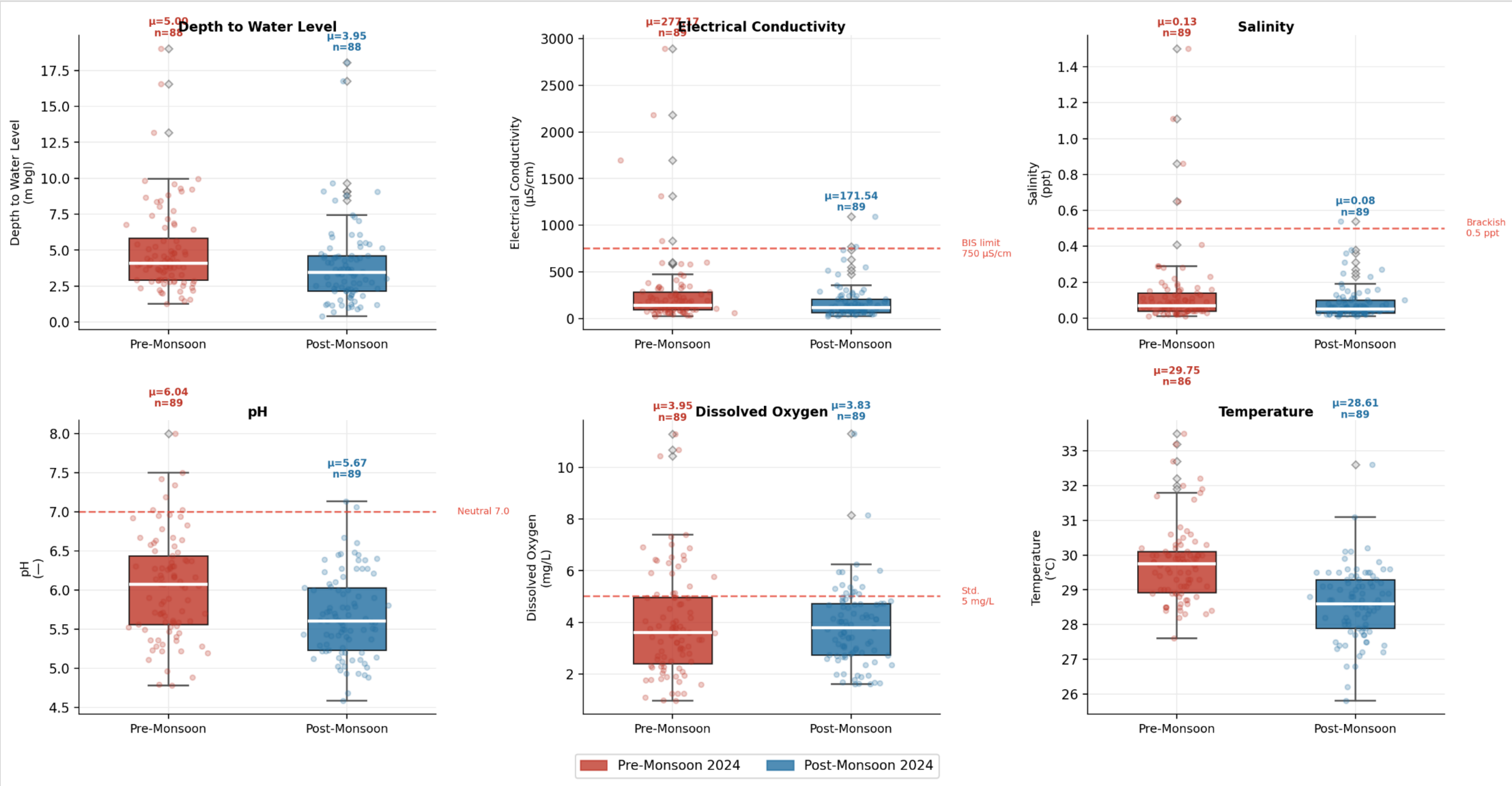


Figure 10: Hydrochemical parameters of observation wells in the study area

6.3 Stable Isotope Parameters

6.3.1 Isotopic Composition of Groundwater — Seasonal Comparison

The isotope results from observations wells in the study area are analyzed and the results are plotted in Figure 11 for further interpretations as below,

The measured stable isotopic composition of groundwater during the pre-monsoon season was in the range of −2.5 to +0.8‰ (average ± standard deviation: −1.6 ± 0.6‰) for $\delta^{18}O$ and −9.0 to +7.3‰ (−4.1 ± 2.8‰) for δ^2H (n=89). The $\delta^{18}O$ and δ^2H values in groundwater samples during the post-monsoon season were in the range of −4.1 to −1.5‰ (−2.2 ± 0.4‰) and −22.3 to −0.1‰ (−7.6 ± 3.4‰) respectively.

The observed isotopic range in this study is much wider than the range previously reported for groundwater of Goa ($\delta^{18}O$ = −2.03 to −1.65‰; δ^2H = −8.26 to −0.56‰; n=10, CGWB OASIS-G data). The isotopic signatures of groundwater samples in North Goa were similar to those reported for the southwest coast of India in Karnataka and Kerala stretches (Tripti et al., 2019), suggesting that the groundwater in North Goa is largely influenced by the summer monsoon rainfall which is dominant in the region.

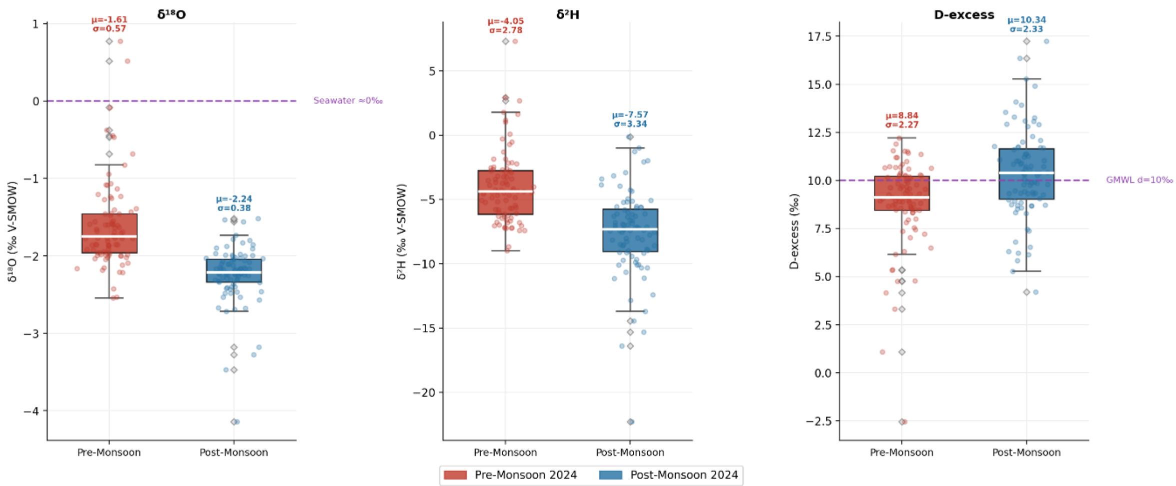


Figure 11: Stable isotope parameters of observation wells

6.3.2 Deuterium Excess (D-excess)

The calculated Deuterium Excess (D-excess) was in the range of −2.5 to 12.2‰ (8.8 ± 2.3‰) during the pre-monsoon season, while it was in the range of 4.2 to 17.2‰ (10.3 ± 2.3‰) during the post-monsoon season. The D-excess values suggest relatively less evaporation effect during post-monsoon than pre-monsoon season. The isotopic composition and D-excess values confirm that groundwater in North Goa had its recharge source from summer monsoon rainfall.

A few samples had D-excess greater than 10‰ indicating terrestrially recycled water source or the winter monsoon effect. One rainwater sample collected during the post-monsoon season showed lower isotope ratios and a very high D-excess value of approximately 20‰. The higher D-excess values observed in different water resources during the summer and winter monsoon seasons at locations further south in Karnataka were attributed to higher continental moisture recycling effects (Tripti et al., 2016), a process that appears to extend into the North Goa region.

6.4 Saline intrusion assessment from bivariate plot ($\delta^{18}O$ vs $\delta^{2}H$)

From the critical saline intrusion diagnostic chart Figure 12. Pre-monsoon samples show a wider spread and shift towards the seawater end-member (+0, 0‰), while post-monsoon samples cluster closer to the GMWL, confirming seasonal dilution. The evaporative trend (deviation below GMWL) in PRM samples indicates significant evaporation-driven enrichment in shallow lateritic wells before monsoon onset. Both seasons confirm predominantly meteoric recharge origin, but the PRM season clearly shows saline mixing influence in a subset of coastal wells.

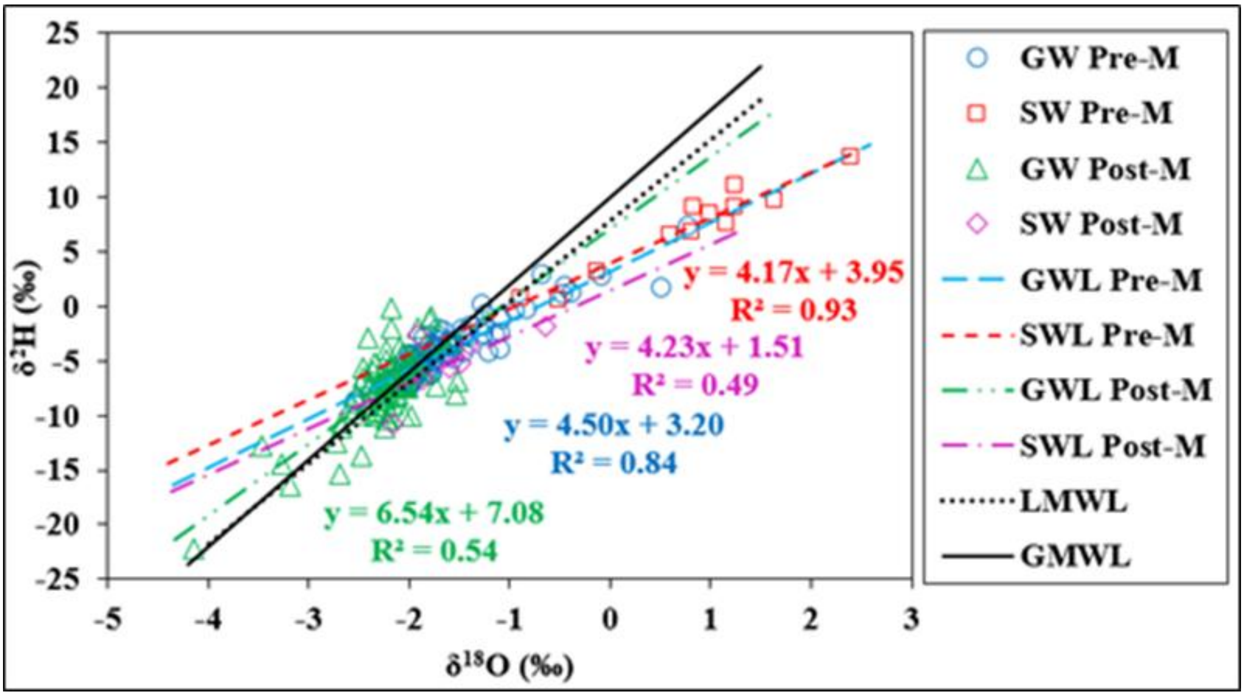
The best fit line obtained for the groundwater (n=89) and surface water (river water, n=8 and lake water, n=2) in the coastal sites of North Goa during pre-monsoon season were respectively: $\delta^2H = (4.50 \times \delta^{18}O) + 3.20$, $R^2 = 0.84$ and $\delta^2H = (4.17 \times \delta^{18}O) + 3.95$, $R^2 = 0.93$. For the case of post-monsoon season, the best fit line of groundwater (n=89) and surface water (river water, n=6 and lake water, n=1) were respectively: $\delta^2H = (6.54 \times \delta^{18}O) + 7.08$, $R^2 = 0.54$ and $\delta^2H = (4.23 \times \delta^{18}O) + 1.51$, $R^2 = 0.49$. This suggests that the evaporation effect on groundwater is reduced during the post-monsoon season relative to pre-monsoon season due to higher recharge by the monsoon rainfall. The surface water line showed higher slope during the post-monsoon season (much higher when one Lake Sample excluded; not drawn here) suggesting less tidal influence in the estuarine region during the average discharge flow season. The best fit line for overall groundwater of Bardez and Tiswadi taluks of North Goa district during 2024 was found to be: $\delta^2H = (5.26 \times \delta^{18}O) + 4.32$, $R^2 = 0.73$, n= 178 (refer Figure 12).

Saline water intrusion signature by Salinity and Isotopic enrichment

In both seasons, a positive correlation between EC and $\delta^{18}O$ is observed from Figure 13 (higher EC = enriched in heavy isotope content = more saline influence), which is the expected signature of seawater mixing. The relationship is stronger in PRM (r ≈ higher), confirming that the pre-monsoon season represents peak saline intrusion conditions. Wells exceeding EC = 750 µS/cm invariably show higher $\delta^{18}O$ values, validating the isotope approach for saline zone identification.

Saline mixing indicator using Deuterium Excess

The bar chart Figure 14 shows that most wells have D-excess below 10‰ in the pre-monsoon season, indicating evaporative enrichment and/or saline mixing. Several wells show D-excess values between 5–8‰ in PRM that recover to near or above 10‰ in POM, these represent seasonally stressed wells where saline influence recedes post-monsoon. A small number of wells show consistently low D-excess across both seasons, indicating persistent saline conditions that are entrants for containment interventions under the NAQUIM 2.0 management plan.



GMWL represents the global meteoric water line while LMWL represents the local meteoric water line. GWL Pre-M, SWL Pre-M, GWL Post-M, and SWL Post-M represents the groundwater and surface water isotopic trend for two different seasons respectively.

Figure 12: Plot showing relationship between $\delta^{18}O$ and δ^2H in groundwater and surface water samples.

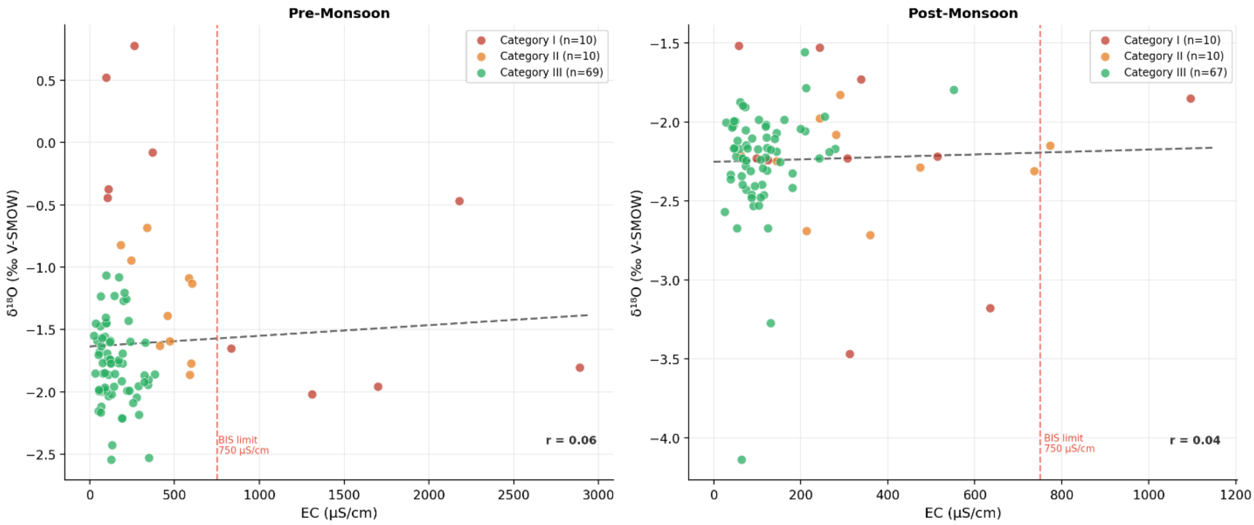


Figure 13: EC vs $\delta^{18}O$ relationship for the study area

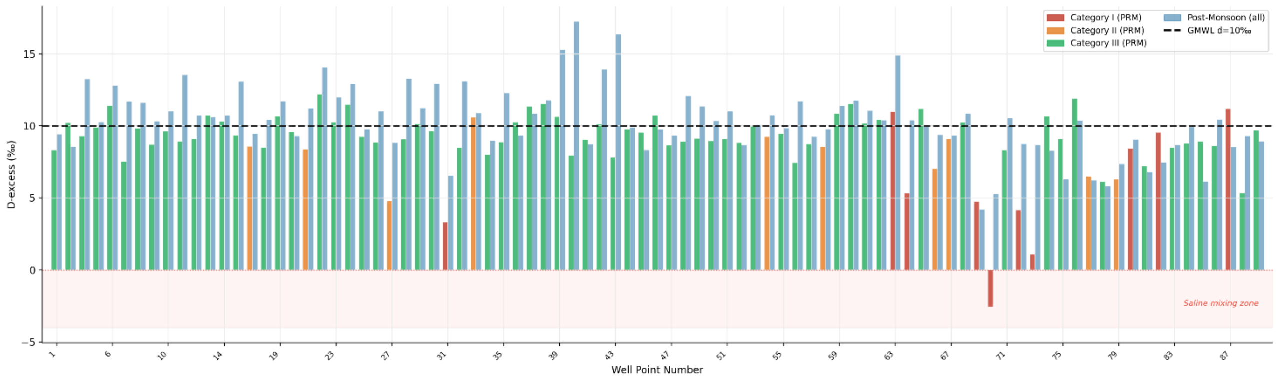
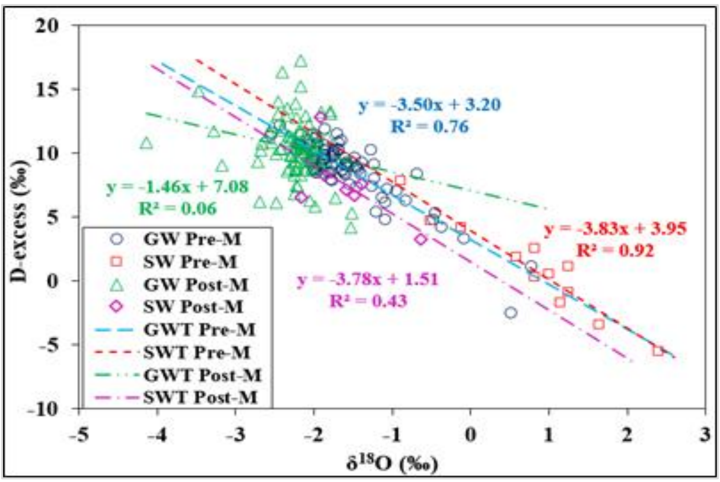


Figure 14: Deuterium Excess for the observation wells in the study area



GWT Pre-M, SWT Pre-M, GWT Post-M, and SWT Post-M represent the groundwater and surface water trend

Figure 15: Plot showing relationship between stable isotope ratios of oxygen and D-excess in groundwater samples

The relationship of stable isotope ratios of oxygen with D-excess in groundwater and surface water confirmed that the pre-monsoon samples showed heavy isotopic enrichment in line with the evaporation effect while that of the post-monsoon season showed less evaporation effect (Figure 15). Most post-monsoon samples clustered together indicating freshly recharged groundwater. The river water samples at coastal stretches showed evaporative enrichment of heavy isotopic content compared to the groundwater during the post-monsoon; however, it was of much lower effect than the pre-monsoon season. Further, the high EC in both river water and groundwater suggested the influence of saline ingress via tidal influence in the estuarine zone during pre-monsoon season. The lake samples also showed backwater effects in this coastal zone. The lake water showed the higher evaporation effect in both seasons compared to groundwater and river water indicating that the large surface area exposure led to higher isotopic exchange with warmer atmosphere.

Spatial variability of groundwater isotopic composition in the study area: The $\delta^{18}O$ and $\delta^{2}H$ values are spatially interpolated and mapped to delineate zones of isotopically enriched (saline-influenced) and depleted (fresh recharge-dominated) groundwater, enabling visual representation of the lateral extent of saline intrusion across the study area. The fresh water zones are marked with lower isotope ratios and higher D-excess, transitional (mixing) zones are marked with mid-higher isotope ratios with average D-excess values while the saline-dominated groundwater zones are marked with higher isotope ratios and very low D-excess values. The spatial plots were also useful in tracing the groundwater and surface water interaction zones. These zones showed higher isotopic composition mainly due to tidal influence on river water during the pre-monsoon season. The groundwater in the shoreline had sea water intrusion effect mainly in the central coastal stretch of study area during the pre-monsoon season. The integrated isotopic and hydrochemical data fingerprinted that the north eastern part of the study area hosted freshwater zones during both seasons. The aquifer in this region must be protected for future water security while considering urban development with increasing tourism pressure in North Goa.

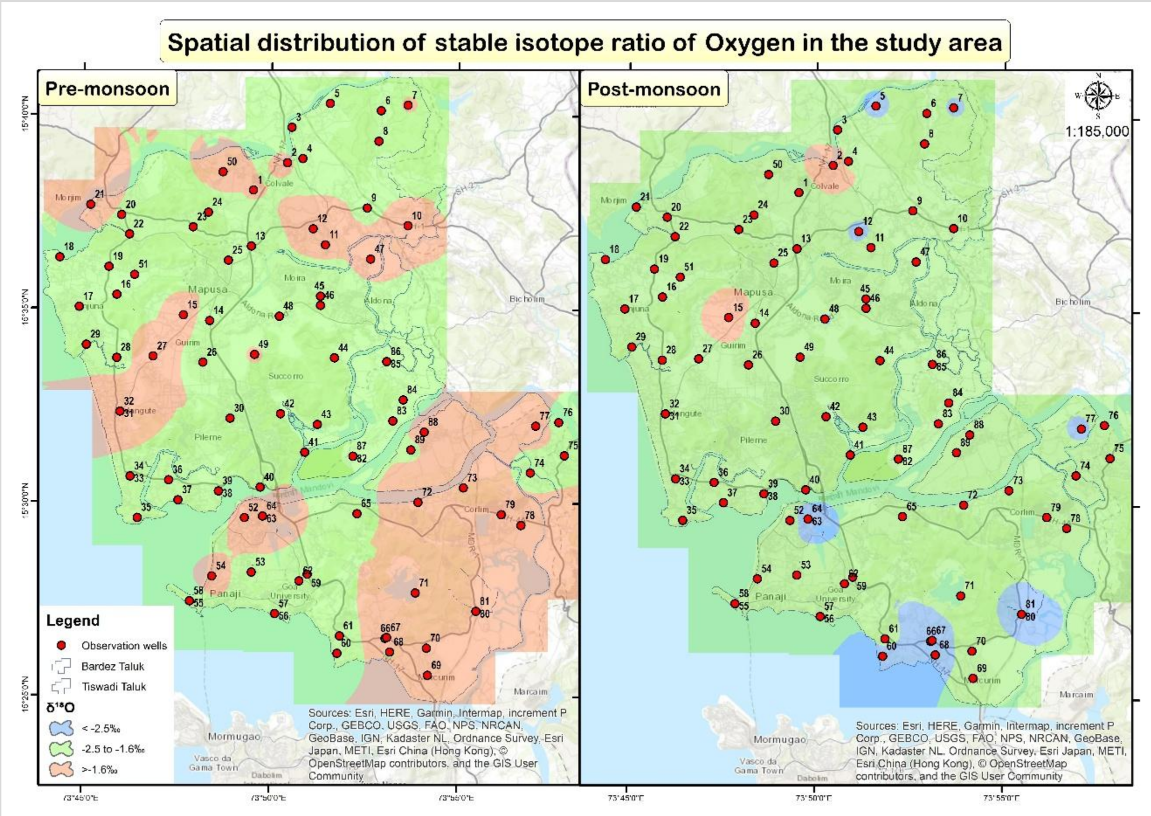


Figure 16: Spatial distribution of $\delta^{18}O$ of groundwater samples

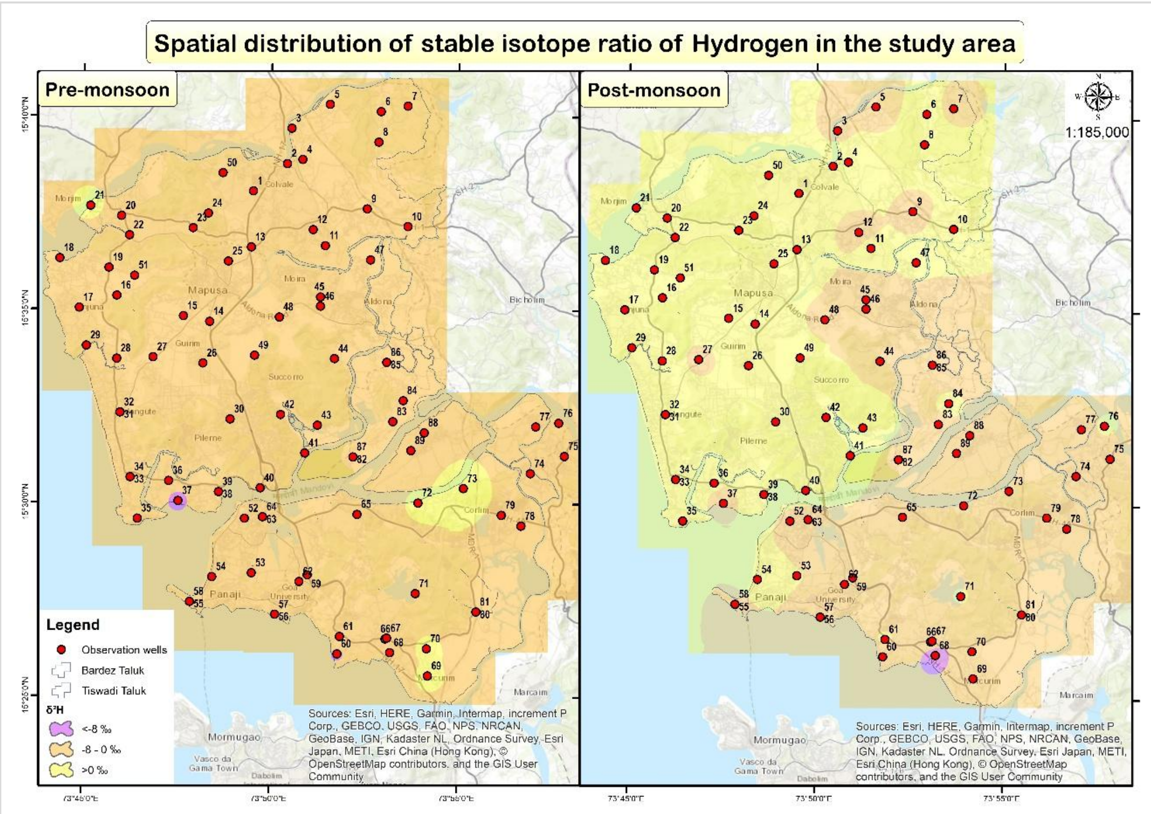


Figure 17: Spatial distribution of $\delta^{2}H$ of groundwater samples

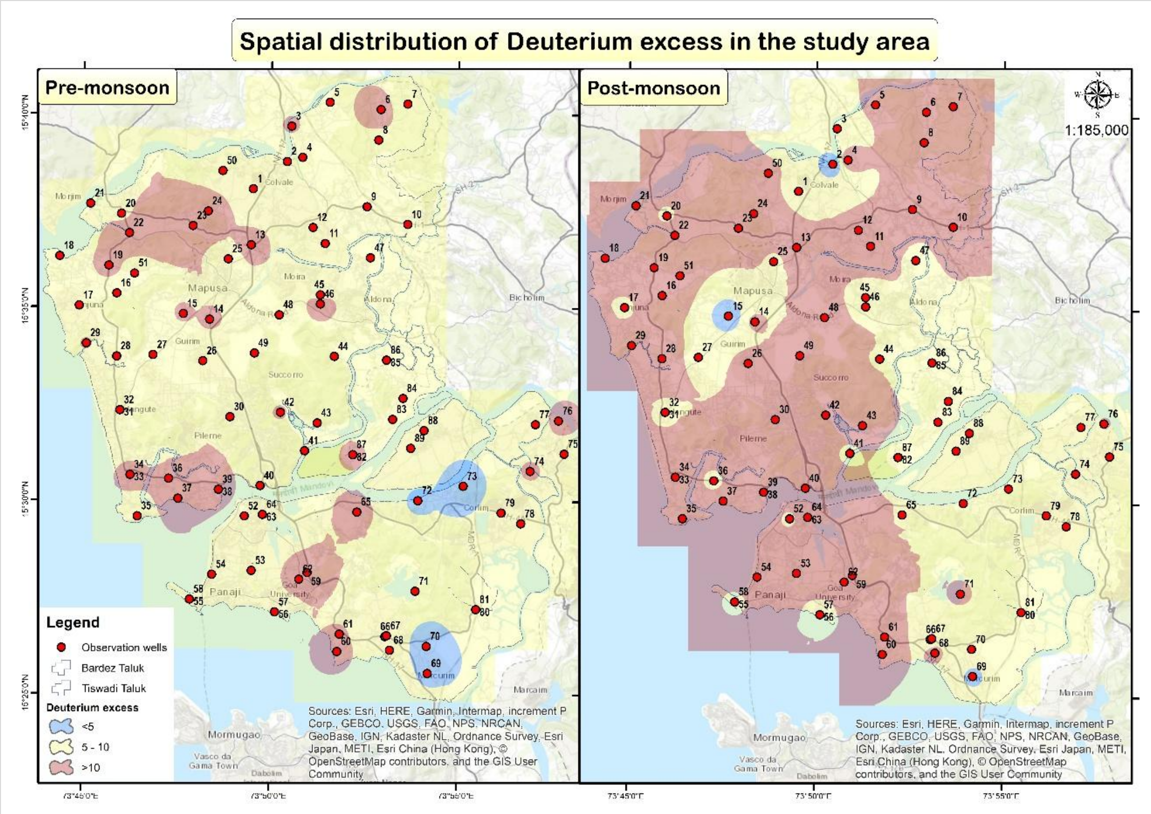


Figure 18: Spatial distribution of D-excess in the study area

6.5 Identification of zones affected by and Vulnerable to Saline Water Intrusion

6.5.1 Classification Criteria

Based on an integrated assessment of EC, TDS, Salinity, $\delta^{18}O$, $\delta^{2}H$ and d-excess data from both sampling seasons, the 89 sampled wells are classified into three categories:

Category I: Actively Affected: Wells showing clear, multi-parameter evidence of ongoing saline water intrusion during the pre-monsoon season, with partial to no recovery post-monsoon. Defined by EC > 750 µS/cm (PRM) and/or Salinity > 0.5 ppt (PRM) and/or $\delta^{18}O > -0.5‰$ (PRM) and post-monsoon values remaining elevated above fresh groundwater baseline.

Category II: Seasonally Vulnerable: Wells showing elevated salinity indicators in the pre-monsoon season that substantially recover post-monsoon, indicating seasonal saline influence that does not fully persist through the monsoon recharge cycle. Defined by EC 400–750 µS/cm (PRM) or Salinity 0.2–0.5 ppt (PRM) OR $\delta^{18}O$ −1.0 to −0.5‰ (PRM) with post-monsoon recovery to near-fresh values.

Category III: Fresh / Minimally Influenced: Wells showing consistently low EC (< 400 µS/cm), Salinity (< 0.2 ppt) and isotopically depleted or GMWL-consistent $\delta^{18}O$ values in both seasons. These represent the safe freshwater aquifer pockets in the study area.

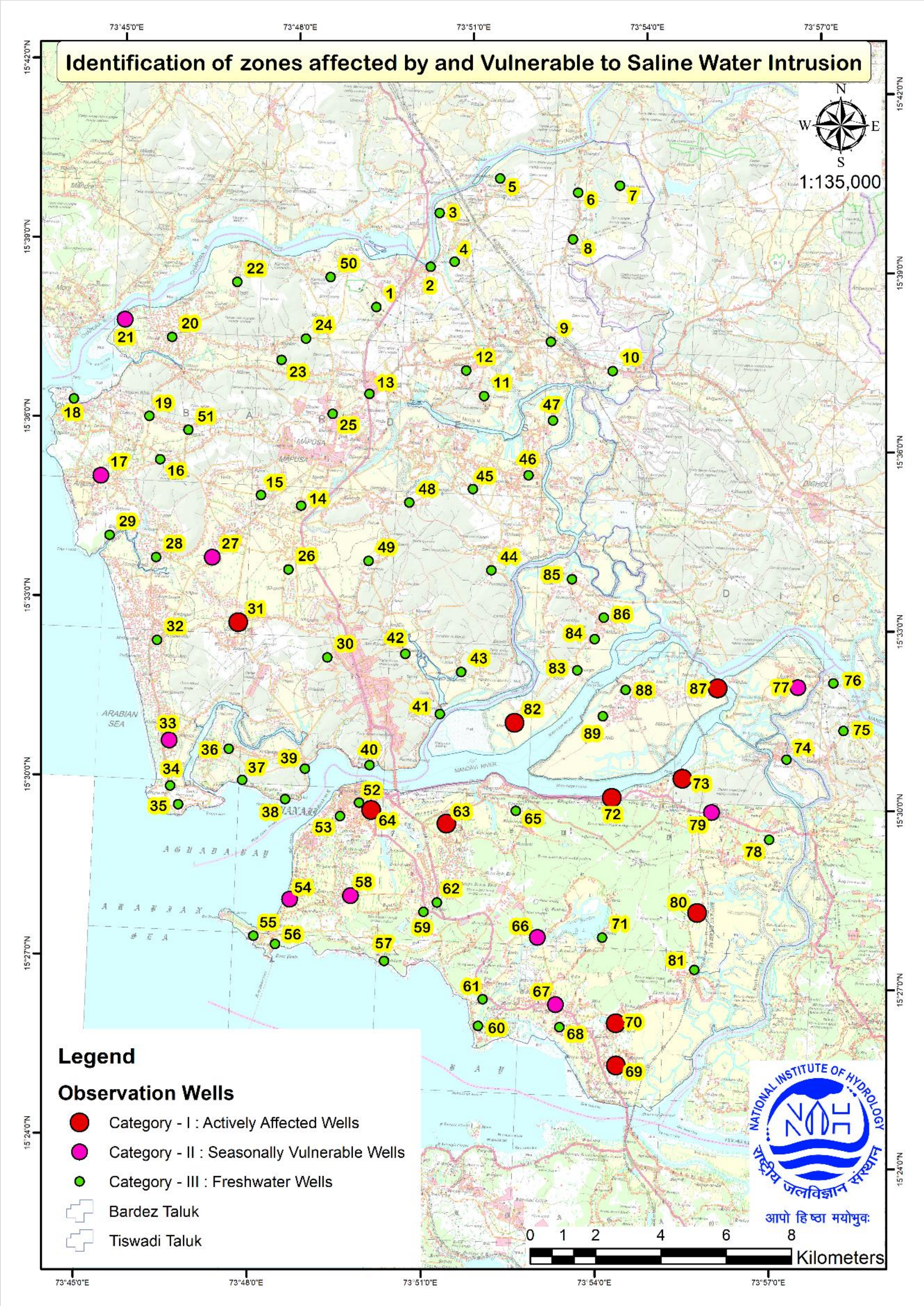


Figure 19: Saline water affected zoned by observation well categories

6.5.2 Category I - Actively Affected Wells

Approximately 10 wells (~11% of the sampled network) meet the Category I criteria. These include well location numbers which showed clear deviation from both the GMWL and LMWL towards the evaporation/saline mixing line on the $\delta^{18}O$–$\delta^{2}H$ plot during the pre-monsoon season. These wells are characterized by:

- Pre-monsoon EC exceeding 750 µS/cm (maximum 2,890 µS/cm, nearly four times the BIS limit).
- Pre-monsoon TDS exceeding 500 mg/L (maximum 1,477 mg/L).
- Pre-monsoon Salinity above 0.5 ppt (maximum 1.5 ppt, brackish groundwater classification).
- Pre-monsoon $\delta^{18}O$ values approaching or exceeding −0.5‰ V-SMOW (maximum +0.78‰), indicating saline water mixing.
- Pre-monsoon D-excess below 6‰, in some cases approaching negative values.
- Post-monsoon persistence of elevated EC and salinity, with incomplete return to fresh baseline conditions.

Table 3: Key Parameters for Category I Wells Actively Affected by Saline Intrusion.

EC PRM (µS/cm)	TDS PRM (mg/L)	Sal PRM (ppt)	$\delta^{18}O$ PRM (‰)	D-excess PRM (‰)	EC POM (µS/cm)	Status
> 2890	> 1477	> 1.5	+0.78	< 5‰	Elevated	Highly Affected
750–2890	500–1477	0.5–1.5	−0.5 to +0.78	5–8‰	Partial recovery	Affected

Spatially, Category I wells are concentrated along:

(a) Some zones in the tidal river fringes of the Zuari, Mandovi and Chapora rivers, where groundwater–tidal river interaction is the dominant salinity mechanism;

(b) Some zone along the shoreline zone of the central coastal stretch of the study area, where limited direct seawater intrusion is also operative.

The primary mechanism of inland saline influence is tidal backwater ingress via the Zuari, Mandovi and Chapora estuaries, which lowers freshwater river discharge during the pre-monsoon season and allows tidal saline water to penetrate deeply into the estuarine stretches, directly influencing groundwater in adjacent shallow phreatic aquifers.

Table 4: Category I Wells that are Actively Affected by Saline Water Intrusion (n=10)

Pt.No	EC PRM	Sal PRM	d18O PRM	d2H PRM	D-exc PRM	EC POM	Sal POM	d18O POM	Status	Field Notes
73	263	0.20	0.777	7.309	1.09	307	0.15	-2.231	**Highly Affected**	isotopically marine
70	98	0.04	0.522	1.639	-2.53	58	0.03	-1.517	**Highly Affected**	d18O >0 confirms marine mixing
80	2890	1.50	-1.806	-6.007	8.44	635	0.31	-3.179	**Highly Affected**	max EC 2890; garden use; persistent POM EC 635
69	2180	1.11	-0.467	1.015	4.75	244	0.11	-1.530	**Actively Affected**	EC 2180; enriched isotopes; partial recovery
87	1699	0.86	-1.959	-4.483	11.19	1096	0.54	-1.852	**Actively Affected**	Highest post-monsoon EC (1096); persistent brackish; no recovery
82	1311	0.65	-2.019	-6.611	9.54	514	0.25	-2.220	**Actively Affected**	partial POM recovery; still above BIS limit
63	835	0.41	-1.652	-2.228	10.99	313	0.15	-3.468	**Affected**	good POM recovery
31	370	0.18	-0.081	2.677	3.32	339	0.16	-1.731	**Affected**	d18O >-0.5; low d-excess
72	110	0.05	-0.375	1.159	4.16	99	0.05	-2.231	**Affected**	d18O >-0.5 trigger; low d-excess PRM; estuarine zone
64	105	0.05	-0.445	1.784	5.34	124	0.06	-2.242	**Affected**	d18O >-0.5

* *Red cells = exceeds critical threshold | Orange = elevated | Green = improved post-monsoon. Pt.73 and Pt.70 identified by d18O > 0 per mil (marine mixing signature). Pt.80, 69, 87, 82 identified by EC/Salinity thresholds. Pt.87 has highest persistent post-monsoon EC (1096 uS/cm).*

6.5.3 Category II - Seasonally Vulnerable Wells

Approximately 10 wells (11.2% of the sampled network) are classified as seasonally vulnerable. These wells show pre-monsoon EC between 400–750 µS/cm, moderate isotopic enrichment ($\delta^{18}O$ −1.0 to −0.5‰) and D-excess between 7–9‰, recovering towards fresh conditions (EC < 400 µS/cm; D-excess ≈ 10‰) in the post-monsoon season. These wells form a spatial transition belt surrounding the Category I core zone and represent the expanding saline fringe that is currently held at bay by annual monsoon recharge. Without management interventions particularly artificial recharge and abstraction regulation these wells are at risk of transitioning into Category I status over the medium term, especially if monsoon recharge patterns become less reliable under climate change or if groundwater abstraction for the tourism sector continues to increase.

Table 5: Category II Wells that are Seasonally Vulnerable (n=10)

Pt.No	EC PRM	Sal PRM	d18O PRM	D-exc PRM	EC POM	Sal POM	d18O POM	POM Recovery	Remarks
77	604	0.29	-1.129	6.50	213	0.10	-2.690	**Partial**	Moderate EC; d18O -1.1; both d-excess below 7; watch zone
33	590	0.28	-1.861	10.60	773	0.38	-2.150	**No Recovery (POM worse)**	POM EC 773 > PRM EC 590, escalating; priority intervention needed
27	584	0.28	-1.086	4.78	737	0.36	-2.312	**No Recovery (POM worse)**	POM EC 737 > PRM 584 escalating; very low d-excess PRM (4.78)
58	598	0.29	-1.773	8.55	474	0.23	-2.287	**Partial**	EC elevated both seasons
17	412	0.19	-1.629	8.57	281	0.13	-2.081	**Good**	EC 412; d18O in transition range; good seasonal recovery
67	473	0.23	-1.593	9.10	359	0.17	-2.717	**Good**	adequate recovery
54	458	0.22	-1.389	9.26	244	0.11	-1.977	**Good**	good freshening post-monsoon
21	338	0.16	-0.682	8.38	291	0.14	-1.828	**Moderate**	d18O -0.68 (near Cat I threshold); POM moderately better
66	245	0.12	-0.944	7.02	144	0.07	-2.248	**Good**	d18O -0.94; good recovery; monitor
79	183	0.09	-0.823	6.30	63	0.03	-2.212	**Good**	d18O -0.82; low d-excess PRM; excellent POM recovery

* *Pt.33 and Pt.27 show post-monsoon EC higher than pre-monsoon EC (highlighted red) so these wells are worsening and may require immediate monitoring and managed recharge interventions. Recovery column: Green = good seasonal recovery; Orange = partial; Red = no recovery / worsening.*

6.5.4 Category III - Fresh Wells

The majority of sampled wells approximately 77.5% are classified as Category III fresh wells, characterized by low EC (< 400 µS/cm), salinity (< 0.2 ppt) and isotopically depleted $\delta^{18}O$ values consistent with fresh monsoon recharge in both seasons. These wells are predominantly located in the inland and plateau zones of eastern Bardez and the north-eastern sector of the combined study area, which emerged as the most reliable and seasonally stable freshwater zone. These locations represent the safe aquifer pockets of highest importance for future drinking water supply development and for the design of groundwater management protection zones under the NAQUIM 2.0 management plan.

Table 6: Category III - Fresh Wells (n=69 total; top 20 most depleted shown)

Pt.No	EC PRM (uS/cm)	Sal PRM (ppt)	d18O PRM (per mil)	d18O POM (per mil)	D-exc PRM
37	125.0	0.06	-2.543	-2.512	11.36
22	131.2	0.06	-2.426	-2.105	12.21
60	349.0	0.17	-2.529	-3.274	11.55
6	50.2	0.02	-2.153	-2.085	11.41
74	190.1	0.09	-2.212	-2.304	10.67
36	187.2	0.09	-2.210	-2.157	10.27
46	291.0	0.14	-2.184	-1.977	10.71
39	65.1	0.03	-2.164	-2.094	10.64
5	67.4	0.03	-2.116	-2.217	9.90
62	254.0	0.12	-2.089	-2.395	10.42
19	275.0	0.13	-2.045	-1.994	10.67
4	109.2	0.05	-2.035	-1.905	9.31
16	129.5	0.06	-2.018	-2.244	9.35
57	97.6	0.04	-1.999	-2.231	8.77
38	73.2	0.03	-1.997	-2.140	11.53
84	54.5	0.03	-1.993	-2.302	8.77
29	234.0	0.11	-1.992	-2.039	10.16
18	219.0	0.10	-1.990	-2.150	8.50
65	86.9	0.04	-1.984	-2.255	11.20
86	54.4	0.02	-1.983	-2.130	8.63

Table 7: Summary of Well Classification -- Bardez and Tiswadi (n=89)

Category	Description	Wells	%	EC PRM Range	d18O PRM Range	Priority Action
I Actively Affected	Confirmed saline intrusion; partial/no POM recovery; 3 wells d18O >0	**10**	11.2%	98 - 2890 uS/cm	-1.96 to +0.78	Immediate abstraction control
II Seasonally Vulnerable	Elevated PRM; partial recovery POM; 2 wells worsening (Pt.27, Pt.33)	**10**	11.2%	183 - 604 uS/cm	-1.86 to -0.68	Managed aquifer recharge + monitoring
III Fresh / Safe	Consistently fresh both seasons; safe aquifer pockets; NE sector dominant	**69**	77.5%	25 - 400 uS/cm	-2.54 to -1.00	Protect + prioritise for supply
TOTAL WELLS		**89**	100%	25 - 2890 uS/cm	-2.54 to +0.78	

Isotope Analysis Inferences

The following inferences are made from the isotope analysis and the results as discussed above,

a) Wide isotopic variation was observed ($\delta^{18}O$: −2.54 to 0.78‰; $\delta^{2}H$: −8.98 to 7.31‰), much broader than earlier data history for Goa, indicating diverse recharge sources and processes.

b) Most groundwater samples align with the Global Meteoric Water Line (GMWL), confirming meteoric origin and minimal post-recharge modification.

c) Few samples (Nos. 31, 64, 69, 70, 72, 73, 79) deviate from GMWL and LMWL, trending toward the evaporation line, implying evaporative enrichment or saline mixing.

d) River (estuarine) and lake waters also exhibit evaporative isotopic signatures, supported by high electrical conductivity at Spots, supporting saline influence in coastal zones.

e) The lower slopes of the best-fit lines for groundwater (4.51) and river water (4.17) compared to the GMWL slope (8) highlight strong evaporative effects and groundwater–surface water interaction in coastal North Goa.

f) Isotope signatures ($\delta^{18}O$ and $\delta^{2}H$) confirm meteoric origin of groundwater, with evaporative enrichment and saline mixing evident near coastal and estuarine zones.

g) Deviation from the Global Meteoric Water Line (GMWL) indicates strong evaporation effects and groundwater–surface water interaction, particularly in coastal Tiswadi.

6.6 Integrated Discussion

6.6.1 Nature and Mechanism of Saline Intrusion in the Study Area

The integrated analysis of hydrochemical and stable isotope data provides a scientifically robust characterization of the nature, extent and mechanisms of saline water intrusion in the coastal aquifers of Bardez and Tiswadi taluks. The evidence points to a multi-mechanism saline intrusion system driven by the following primary processes:

a) Direct seawater intrusion from the Sea: Confirmed by isotopically enriched pre-monsoon $\delta^{18}O$ values approaching the seawater end-member, particularly in wells within 1–2 km of the shoreline in western Bardez (Calangute–Candolim sector). The positive EC–$\delta^{18}O$ correlation validates the marine origin of dissolved salts in these wells.

b) Tidal backwater and estuarine influence from the Zuari, Mandovi and Chapora rivers: Wells proximal to the tidal reaches of these rivers, particularly along the Panaji and Ribandar waterfronts of Tiswadi and in the Siolim-Chopdem sector of Bardez show elevated salinity indicators that are more consistent with brackish tidal water mixing than with direct open-sea intrusion. The shallow phreatic lateritic aquifer in these zones is hydraulically directly connected to the tidal river systems.

c) Evaporative enrichment in shallow lateritic wells: The below-GMWL deviation of pre-monsoon isotopic data on the $\delta^{18}O$–$\delta^{2}H$ bivariate plot and the suppressed pre-monsoon d-excess values (mean 8.84‰ vs GMWL value of 10‰) confirm that shallow water table depths (< 3 m bgl) combined with the prolonged dry season result in significant evaporative concentration of groundwater before monsoon onset, further elevating EC, TDS and Salinity readings in the pre-monsoon dataset.

6.6.2 Seasonal Dynamics and Recovery

The comparison of pre-monsoon and post-monsoon datasets reveals a clear and consistent pattern of seasonal saline influence followed by partial to full monsoon-driven freshening across the majority of the aquifer system. The mean seasonal improvement in EC (-38%), TDS (-42%), Salinity (-40%) and $\delta^{18}O$ (-0.63‰) between PRM and POM seasons confirms that monsoon recharge is currently the dominant mechanism of annual aquifer freshening in the study area.

However, the persistence of elevated salinity indicators in Category I wells even after the full monsoon season is a critical finding. It suggests that the natural freshening capacity of the monsoon recharge system is being outpaced by the rate of saline ingress in the most affected locations, a condition likely driven by excessive groundwater abstraction during the nine-month dry season for tourism and domestic supply. If this imbalance is not corrected through management interventions, progressive deepening and spatial expansion of the saline intrusion zone can be anticipated over the coming years.

6.6.3 Implications for Urban and Tourism Water Security

The study area encompasses the most intensively urbanized and tourism-developed coastal belt of Goa, including Panaji (the state capital, in Tiswadi taluk), the beach resort villages of Calangute, Candolim, Baga, Anjuna and Vagator in Bardez, and the associated road, hospitality and infrastructure network that supports approximately 8 million domestic and international tourist visits annually. Per capita water availability in Goa has declined from approximately 4,500m^3 per capita in 1980 to approximately 2,200m^3 at present, and the coastal belt already faces a documented water supply deficit of 85 million litres per day.

The finding that approximately 9–11% of wells in the study area are actively affected by saline intrusion and a further 13–18% are seasonally vulnerable has direct and urgent implications for this water security context. A significant number of the affected wells correspond to dug wells and borewells in the coastal tourism belt that are either used directly for non-potable hotel and resort operations or serve as source wells for private water tanker distribution, a network that supplements the chronically deficient municipal supply. The contamination of these sources by saline water not only compromises water quality for domestic and commercial use but also accelerates corrosion of plumbing infrastructure in the resort sector and threatens the viability of horticultural and small-scale agricultural activities in the coastal zone.

6.6.4 Implications for NAQUIM 2.0 Aquifer Management Planning

The integrated dataset generated by this NIH study directly informs the NAQUIM 2.0 aquifer management plan being prepared by CGWB for Bardez and Tiswadi taluks. The key management inputs from this investigation include:

a) Identification of Category I saline intrusion hotspots for immediate abstraction regulation and consideration of emergency supply augmentation through alternative sources or treated water.
b) Delineation of Category III fresh-water aquifer pockets in inland locations that are suitable for prioritized development as drinking water supply sources, reducing reliance on the stressed coastal aquifer belt.
c) Scientific basis for the design of targeted artificial recharge structures — such as percolation ponds, check dams and recharge shafts — at Category II transition zone locations, where augmentation of the freshwater head can effectively push back the saline interface and protect the seasonal recovery trajectory.
d) Identification of the Zuari, Mandovi and Chapora tidal reaches as hydraulically critical zones requiring buffer zone protection and regulated abstraction within defined setback distances from tidal water bodies.

e) Recommendation for continued seasonal monitoring of the key observation wells, using the pre-monsoon and post-monsoon protocol established in this study as part of an operational groundwater quality and saline intrusion monitoring network under NAQUIM 2.0 in the study area.

7 SUMMARY AND CONCLUSIONS

a) The shallow phreatic lateritic aquifer system of Bardez and Tiswadi taluks undergoes a mean seasonal water table recovery of approximately 1.05 m during the observation period between pre-monsoon and post-monsoon seasons, confirming active monsoon recharge to the aquifer system.

b) Pre-monsoon EC (max 2,890 µS/cm), TDS (max 1,477 mg/L) and Salinity (max 1.5 ppt) referring to Figure 10 confirms the presence of brackish to near-saline groundwater in the coastal zone, exceeding BIS drinking water standards at approximately 12–15% of sampled wells.

c) Stable isotope analysis confirms active saline water intrusion at select coastal wells through isotopically enriched pre-monsoon $\delta^{18}O$ values reaching +0.78‰ V-SMOW approaching the seawater isotopic composition with estimated seawater mixing fractions of up to 25–35% at the most affected locations.

d) The $\delta^{18}O$ vs $\delta^{2}H$ bivariate plot (refer Figure 12) demonstrates a clear evaporative enrichment trend in pre-monsoon samples deviating below the GMWL, consistent with shallow water table depths and dry season evaporation in lateritic aquifers.

e) The D-excess analysis (refer Figure 11 and Figure 14) confirms post-monsoon groundwater recharge from sea moisture-derived precipitation (mean POM D-excess 10.34‰ ≈ GMWL), while pre-monsoon depression of D-excess (mean 8.84‰) indicates combined evaporative enrichment and saline mixing.

f) Approximately 9–11% of wells (Category I) show active, persistent saline intrusion; 13–18% (Category II) are seasonally vulnerable; the majority (63–70%, Category III) represent fresh, inland groundwater pockets suitable for drinking water supply.

g) A positive EC–$\delta^{18}O$ correlation (refer Figure 13) in both seasons validates the marine origin of dissolved salts in high-EC wells, confirming that elevated salinity is driven by seawater/tidal water mixing rather than mineral dissolution or anthropogenic inputs.

h) The combination of tourism-driven groundwater over-abstraction, shallow water tables, tidal river connectivity and limited artificial recharge creates a critically vulnerable hydrogeological setting requiring urgent, science-based aquifer management interventions under NAQUIM 2.0.

8 WAY FORWARD / SCOPE FOR FURTHER WORK

The present investigation represents the first systematic isotope-based assessment of saline water intrusion in the Bardez–Tiswadi coastal aquifer system and establishes an important scientific baseline. A number of directions for further scientific development are identified:

i) Extension of the stable isotope dataset to deeper confined or semi-confined aquifer systems, which were not sampled in the present study but may serve as protected freshwater reserves or, alternatively, as conduits for vertical saline migration under abstraction stress.

ii) Integration of geophysical investigations (such as Vertical Electrical Sounding and Electromagnetic profiling) with the isotopic and hydrochemical data to provide three-dimensional delineation of the saline-freshwater interface geometry and enable volumetric estimation of the affected aquifer.

iii) Tritium (^{3}H) and/or radiocarbon (^{14}C) analysis of selected wells to determine groundwater residence times and distinguish between recently recharged, recent anthropogenically influenced and palaeosaline groundwater components.

iv) Monthly and inter-annual monitoring to assess the timing and pattern of saline intrusion status, particularly in the context of changing rainfall patterns and increasing water demand associated with continued tourism and urban expansion.

v) Numerical groundwater flow and solute transport modelling (MODFLOW–MT3D or SEAWAT) using the established hydrochemical and isotopic data as calibration constraints, to enable predictive assessment of saline intrusion under different abstraction and recharge management scenarios.

9 ACKNOWLEDGEMENTS

The National Institute of Hydrology, Hard Rock Regional Centre, Belagavi, places on record its sincere gratitude to the Central Ground Water Board, South Western Region, Bengaluru, and in particular to the Regional Director, CGWB SWR, Bengaluru, for extending the invitation to collaborate in the NAQUIM 2.0 coastal aquifer salinity study in Bardez and Tiswadi taluks, North Goa. The support, cooperation and scientific guidance extended by the Sub-divisional Unit Office (SUO), CGWB, Belagavi, throughout the planning and execution of field investigations is gratefully acknowledged. The facilitation of field logistics, sharing of hydrogeological data and the constructive scientific interactions with the CGWB team have been invaluable in the successful conduct of the study.

The Head, Hydrological Investigations Division, NIH, Roorkee is thanked for the encouragement to take up this study and providing the Nuclear hydrology laboratory facility for isotopic analysis.

10 REFERRED LETTER FROM END-USE AGENCY

सत्यमेव जयते

स्वच्छ सुरक्षित जल – सुन्दर खुशहाल कल
CONSERVE WATER – SAVE LIFE

भारत सरकार
केंद्रीय भूमि जल बोर्ड
जल शक्ति मंत्रालय
Government of India
Central Ground Water Board
Ministry of Jal Shakti

बोर्ड, दक्षिण पश्चिम क्षेत्र/ Central Ground Water Board, South Western Region,
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T/A1/2.1-NAQUIM2.0 -221

Date- 01.03.2024

04 MAR 2024

To,
The Head,
National Institute of Hydrology,
Hard Rock Regional Center,
Main Road, Irrigation Colony,
Visvesvaraya Nagar,
Belagavi – **590019** (Karnataka), India.

Sub: Scope of collaboration with NIH,Belgavi in NAQUIM 2.0 studies of CGWB, SWR, Bangalore

Sir,

National Aquifer Mapping (NAQUIM) is a flagship programme of the Central Ground Water Board(CGWB) under Ministry of Jal Shakti with the objectives of delineating aquifers, characterizing aquifers and preparing aquifer management plans. The NAQUIM **2.0** studies have been initiated since April **2023** after completion of NAQUIM **1.0** with an aim to provide information in higher granularity with a focus on increasing density of dynamic data like ground water level, ground water quality etc., providing issue based scientific inputs for ground water management upto panchayat level, putting in place a strategy to ensure implementation of the recommended strategies and involving state agencies in the studies for a sense of ownership.

During the ensuing year i.e., Annual Action Plan (AAP) 2024-25, this office has planned to take up NAQUIM 2.0 study in **Bardez and Tiswadi taluk,North Goa district** with the objectives mentioned in Annexure-I enclosed with this letter.

In this matter, it will be appreciated if your esteemed organisation i.e., NIH, Belgaum can join hands and collaborate with CGWB, SWR, Bangalore to achieve the scientific objectives which will be helpful in furthering the scientific cause. Your collaboration will be mainly required on the topics **mentioned in point "g", "h", "i"** of Annexure-I. Therefore, it is requested to kindly inform the name and contact details of the Liaison officer, in case NIH is willing to be a part of collaborative studies. Smt.Sangita P.Bhattacharjee, Sc-D from SUO,Belgavi will be visiting your institute for further discussions on this matter.

Looking forward to a positive reply from your end at the earliest as the study will be initiated in April 2024.

Yours faithfully,

(N. Jyothi Kumar)
Regional Director

Copy to:

1. The Member (South), CGWB, NH-IV, Bhujal Bhawan, Faridabad for kind information.

(N. Jyothi Kumar)

ANNEXURE-I

Envisaged Deliverables for NAQUIM 2.0 Studies

Tiswadi and Bardez taluk,North Goa district; Area – **478** sq.km.

a. Aquifer Disposition with GIS based point map of aquifer disposition with attributes
b. Aquifer-wise ground water levels by establishing 95 key wells.
c. Delineation of recharge areas
d. Ground Water Quality studies to identify contaminants and area affected
e. Identification of potential aquifers for drinking water supply
f. Devise implementable management plan
    - Identify feasible areas for artificial recharge, rain water harvesting (storage)
    - Recommend suitable artificial recharge and harvesting (storage) structures
    - Identify areas where micro irrigation techniques can be recommended
    - Recommended interventions for containing saline ingress (Artificial Recharge, Regulation etc.)
    - Ground Water Quality Management Interventions including demarcation of safer aquifers

g. ***Isotope sampling and analysis to identify saline water ingress***
h. ***Bromide sampling and analysis to identify saline water ingress***
i. ***Lateral and Vertical Extent of saline ingress***

CGWB would like to have collaboration with NIH on the studies mentioned in point "g", "h", "i".

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