

**AN INTEGRATED GEO-HYDROLOGICAL APPROACH TOWARDS WATER
RESOURCE DEVELOPMENT PLAN FOR THE ISOLATED ISLANDS IN THE
GREAT RANN OF KACHCHH, GUJARAT, WESTERN INDIA**

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1. ABSTRACT

The Great Rann of Kachchh (GRK), western Gujarat, represents a hyper-arid saline desert environment characterized by low and erratic rainfall (380–420 mm/year) and extremely high evapotranspiration (>2000 mm/year), resulting in severe freshwater scarcity. Khadir Island (~315 km²), the largest inhabited “bet” within the GRK, supports a population of approximately 17,257 and hosts the UNESCO World Heritage site of Dholavira. Groundwater is the primary freshwater source; however, its availability and quality are increasingly threatened by natural salinity, excessive abstraction (Water Exploitation Index: 72.1%), inefficient irrigation practices, and progressive seawater intrusion.

Field investigations conducted during the post-monsoon seasons of 2019 and 2021 revealed substantial spatial variability in groundwater quality, with Total Dissolved Solids (TDS) ranging from 250 mg/L in recharge zones to ~7,200 mg/L in intrusion-affected areas. Hydrochemical indicators, particularly Na⁺/Cl⁻ ratios (<0.86), confirm active seawater intrusion in coastal parts of the island. Long-term monitoring data further indicate significant groundwater-level fluctuations, including seasonal drying of wells and partial recovery during favourable recharge years.

To address these challenges, the present study develops an integrated geo-hydrological framework combining RS–GIS-based Multi-Influencing Factor (MIF) analysis, MODFLOW-6 groundwater flow modelling, SWI2 seawater intrusion simulation, hydrochemical validation, water demand assessment, and material-informed Managed Aquifer Recharge (MAR) planning. Groundwater potential zoning indicates that 8.45% of the island falls under good potential, 90.45% under moderate potential, and 1.10% under poor potential zones. The calibrated groundwater flow model (RMSE: 1.24 m) estimates annual recharge at $\sim 2.45 \times 10^7$ m³, largely balanced by evapotranspiration (48.2%) and coastal outflow (45.7%), indicating a recharge-rich but availability-limited aquifer system.

Seawater intrusion modelling demonstrates progressive inland advancement from ~1.0 km in 2005 to ~6.3 km in 2020 and further to ~7.2 km by 2025, indicating that the aquifer has reached an advanced critical stage of intrusion. Intrusion rates vary between 0.20 and 0.48 km/year, with a relatively reduced rate (~0.18 km/year) observed during 2020–2025. Water demand assessment shows that agriculture contributes more than 99% of total demand, while groundwater availability exhibits strong interannual variability (1,256–2,324 MLY), leading to intermittent deficit conditions. Future projections (2026–2030) using the Water Stress Index (WSI) indicate moderate to critical stress scenarios.

Based on these findings, a 10-year phased water resource development plan (2026–2035) is proposed, incorporating 23 MAR structures supported by site-specific material selection (filter media, geotextiles, and low-permeability barriers), along with demand management, seawater intrusion control, palaeochannel exploration, and livelihood integration strategies. The plan targets approximately 27% reduction in water demand and augmentation of ~90 MLY through recharge interventions.

The study concludes that sustainable groundwater management in Khadir Island requires an integrated approach combining recharge enhancement, abstraction regulation, seawater intrusion mitigation, and material-optimized MAR design. The proposed framework provides a scientifically robust and transferable model for groundwater management in similar arid and island environments under increasing climatic and anthropogenic stress.

2. BRIEF DESCRIPTION ON THE STATE OF THE ART OF THE RESEARCH TOPIC

Groundwater is a critical component of water security in India, contributing approximately **60% of irrigation demand and over 80% of rural drinking water supply** (Freeze & Cherry, 1979; CGWB, 2023). In arid and semi-arid regions, it often represents the **only reliable freshwater source**. However, increasing abstraction pressures, coupled with climate variability, have resulted in widespread aquifer depletion and deterioration of groundwater quality (Famiglietti, 2014). These challenges are particularly acute in **coastal and island aquifers**, where freshwater occurs as a thin lens overlying saline water, making the system highly sensitive to even minor hydraulic perturbations (Werner et al., 2013).

The **Great Rann of Kachchh (GRK)** in western Gujarat is a unique hydrogeological setting characterized by a hyper-arid climate, extreme temperatures (summer >40 °C and winter near freezing), and low, highly variable rainfall (380–420 mm/year). The region comprises elevated landforms known as “bets” (islands), including Pachchham, Khadir, Bela, and Chorar. Among these, **Khadir Island (~315 km²)** is the largest and most socio-economically significant, hosting ten villages with a population of approximately **17,257**, as well as the UNESCO World Heritage site of Dholavira. The ancient water management systems of Dholavira highlight the long-standing challenge of water scarcity in the region.

Despite this historical awareness, contemporary water management practices in the GRK region remain largely **fragmented and reactive**, including reliance on deeper borewells, small-scale recharge structures, and water transportation. Such approaches do not adequately address the complex interactions between geology, recharge processes, seawater intrusion, and water demand dynamics.

Recent advances in groundwater science emphasize the need for **integrated geo hydrological frameworks** that combine:

- (i) Geological and lithological characterization,
- (ii) Climatic and hydrological analysis,
- (iii) Groundwater potential zone (GWPZ) mapping using RS–GIS techniques,
- (iv) Numerical modelling of groundwater flow and seawater intrusion, and
- (v) Socio-economic assessment of water demand and livelihoods.

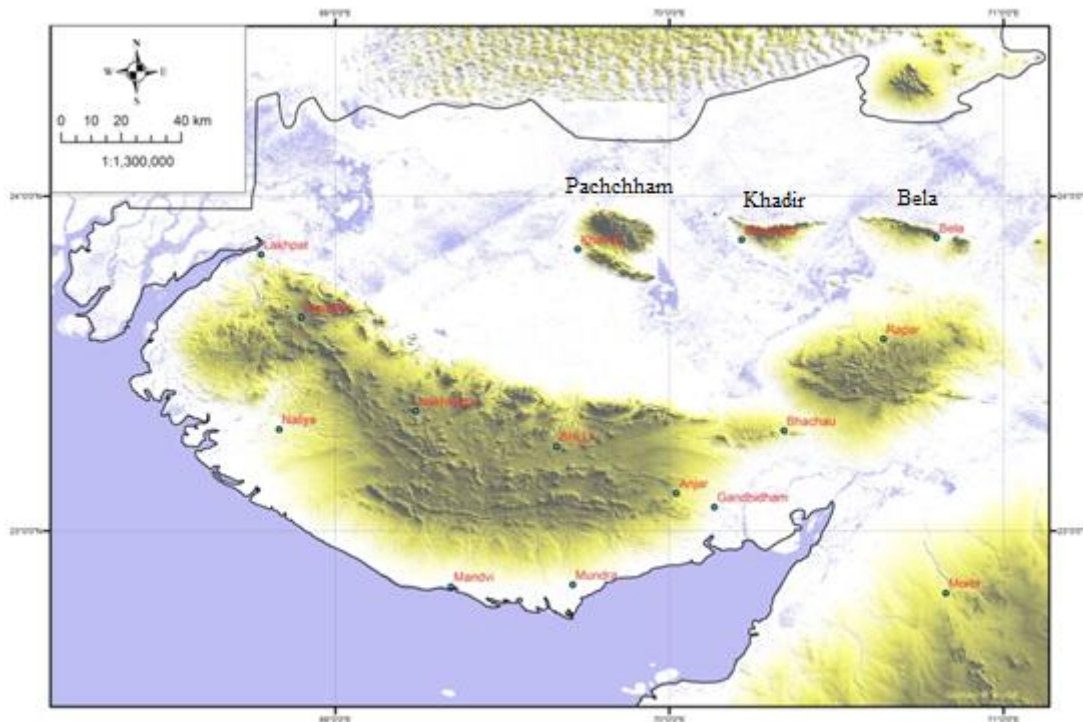


Figure 1: Location of Series Island, Great Rann of Kachchh, Gujarat

However, existing studies in the GRK region are largely **component-specific** and lack integration across these domains. While some work has been carried out in Pachchham Island and mainland Kachchh, **no comprehensive, island-scale integrated study exists for Khadir Island**, despite its larger area, higher population, and greater strategic importance.

Furthermore, Khadir Island exhibits a unique combination of challenges, including **salinity-prone aquifers, increasing groundwater abstraction, irrigation inefficiencies, and progressive seawater intrusion**, making it an ideal case for developing and testing an integrated framework.

Therefore, the present study selects **Khadir Island as the primary study area** and develops an integrated geo-hydrological approach that combines spatial analysis, numerical modelling, hydrochemical validation, and water demand assessment. The outcomes are expected to not only address local water resource challenges but also provide a **replicable**

framework for sustainable groundwater management across other island systems (bets) of the Great Rann of Kachchh.

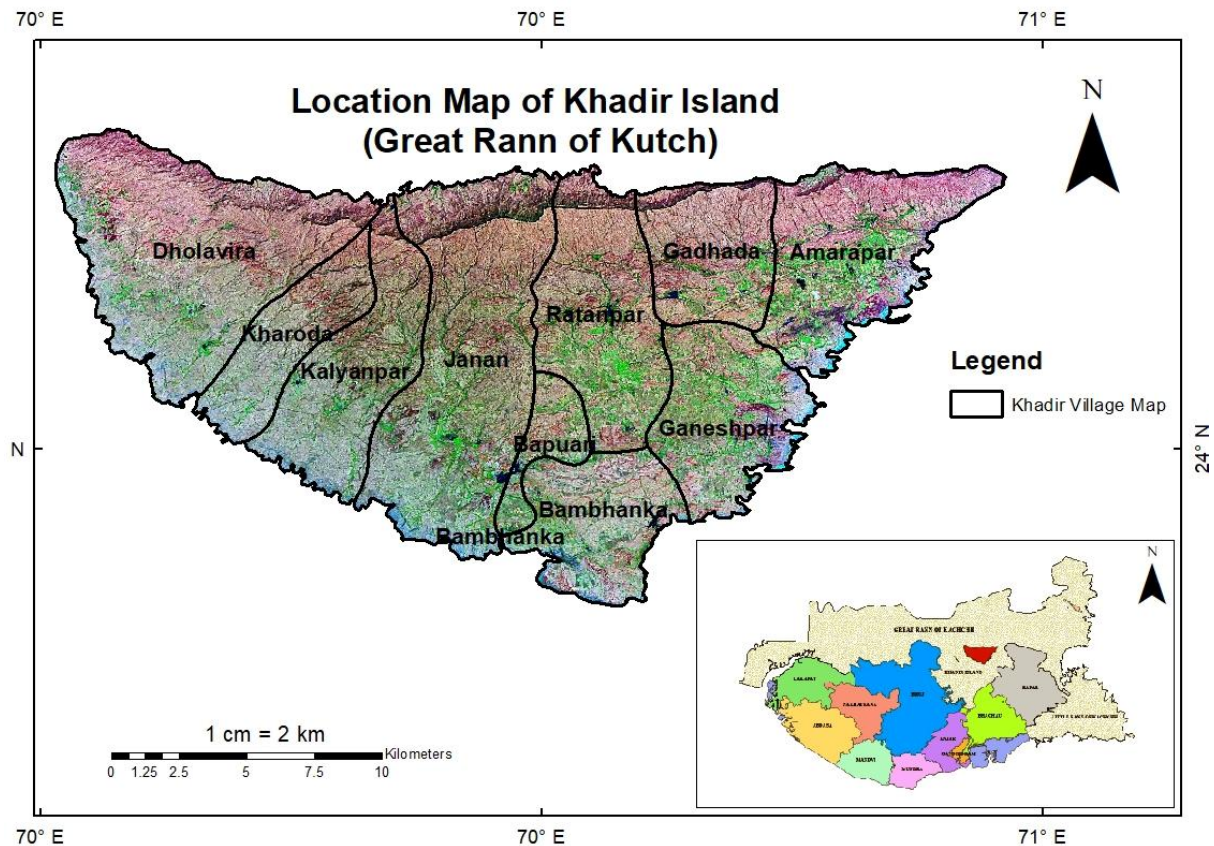


Figure 2: Locational Map of Khadir Island with Village Boundaries.

3. LITERATURE REVIEW

3.1 Groundwater Potential Mapping:

Remote sensing (RS) and Geographic Information System (GIS) techniques have significantly advanced groundwater prospecting. Methods such as the Multi-Influencing Factor (MIF), Analytical Hierarchy Process (AHP), and Frequency Ratio (FR) are widely used for delineating groundwater potential zones (GWPZ). Among these, the MIF method reduces subjectivity compared to AHP and has been successfully applied in diverse Indian hydrogeological settings (Magesh et al., 2012; Das & Pardeshi, 2018). However, no systematic GWPZ mapping has been reported for the island systems of the Great Rann of Kachchh (GRK) prior to this study.

3.2 Managed Aquifer Recharge (MAR):

Managed Aquifer Recharge (MAR) techniques—including check dams, percolation tanks, recharge shafts, and bandharas (tidal regulators)—are widely adopted for enhancing groundwater recharge in water-scarce regions (Dillon et al., 2020). GIS-based multi-criteria

decision analysis is commonly employed for MAR site selection (Aju et al., 2021). In coastal environments, bandharas play a critical role in controlling tidal ingress, and their siting depends on stream geometry and hydraulic conditions (Werner et al., 2013). Despite these advancements, no systematic MAR site selection framework has been developed for the GRK island systems.

3.3 Seawater Intrusion:

Island aquifers are particularly vulnerable to seawater intrusion due to their limited storage and proximity to saline boundaries (Post, 2005). Numerical models such as the SWI2 package for MODFLOW simulate intrusion processes using a sharp-interface approach (Bakker et al., 2013). In India, seawater intrusion has been extensively documented along both western and eastern coastal aquifers (Singaraja et al., 2014; Kushawaha et al., 2024). However, no dedicated seawater intrusion modelling study has been conducted for the GRK island aquifers prior to this research.

3.4 Paleochannels Aquifers:

Paleochannels, representing buried river systems filled with permeable sediments, are recognized as potential freshwater reservoirs in arid regions such as the Thar Desert, Libyan Sahara, and the UAE (Ghose et al., 1979; Francke, 2016; Ishola et al., 2024). In the GRK region, Bhadra et al. (2021) identified paleochannels at depths of 100–150 m using remote sensing and geophysical techniques, containing artesian brackish water (TDS: 2,000–5,000 mg/L). However, no deep borehole investigations have been conducted on Khadir Island to validate these potential aquifers prior to this study.

3.5 Socio-Hydrology and Livelihoods:

Socio-hydrological studies emphasize the dynamic interaction between human activities and water systems. In the GRK region, pastoralist communities (Maldharis) have developed adaptive strategies to cope with water scarcity (Salot & Mehta, 2004). Pastoralism contributes significantly to the regional economy (India Water Portal, 2024), while agriculture occupies approximately 34% of Khadir Island, with bajra as the primary crop. Additional livelihoods include handicrafts and tourism, and recent initiatives such as Piloodi (*Salvadora persica*) cultivation highlight evolving land-use practices (Institute of Rural Management, undated). However, integration of socio-economic factors into hydrogeological planning remains limited.

3.6 Geological Evolution:

The Great Rann of Kachchh is tectonically controlled and bounded by major fault systems. The region experienced a significant marine transgression approximately 18,000 years

ago, resulting in the deposition of fine-grained saline sediments (Maurya et al., 2013). These geological conditions contribute to the inherent salinity of shallow aquifers and strongly influence groundwater occurrence and quality.

3.7 Research Gaps Identified:

Based on the above review, the following key research gaps are identified:

1. Absence of systematic groundwater potential zoning for Khadir Island.
2. Lack of integrated groundwater flow and seawater intrusion modelling.
3. No quantitative assessment of water demand–supply dynamics.
4. Limited validation using hydrochemical data.
5. Absence of a comprehensive, site-specific water resource development framework.

This study uniquely integrates spatial analysis, numerical modelling, hydro chemical validation, and material-informed MAR planning within a single framework.

4. AIM, OBJECTIVES, SCOPE AND LIMITATIONS OF THE STUDY

4.1 Aim of the Study

The primary aim of the present research is to develop an integrated geo-hydrological approach for sustainable water resource development in Khadir Island, located in the Great Rann of Kachchh, Gujarat. The study seeks to address the complex hydrogeological challenges of an arid island environment by integrating geological characterization, spatial analysis, numerical modelling, hydrochemical validation, and water demand assessment into a unified framework for effective and resilient water resource planning.

4.2 Objectives of the Study

To achieve the above aim, the study is structured around the following objectives:

1. **To characterise the geo-hydrological framework:** Analyse the geological, lithological, geomorphological, and hydrogeological conditions of Khadir Island to understand groundwater occurrence, storage, and movement.
2. **To delineate groundwater potential zones (GWPZ):** Apply Remote Sensing (RS) and GIS techniques using the Multi-Influencing Factor (MIF) method to identify spatial variability in groundwater potential.
3. **To simulate groundwater flow dynamics:** Develop a transient three-dimensional groundwater flow model using MODFLOW-6 to evaluate aquifer behaviour under varying recharge and abstraction conditions.
4. **To assess seawater intrusion processes:** Use the SWI2 package to analyse the extent, progression, and dynamics of seawater intrusion in the coastal aquifer system.

5. **To evaluate water demand and supply dynamics:** Quantify sectoral water demand (domestic, agriculture, livestock, and tourism) and assess its relationship with groundwater availability.
6. **To analyse water stress conditions:** Determine the temporal mismatch between water supply and demand using indicators such as the Water Stress Index (WSI).
7. **To develop an integrated water resource development plan:** Formulate a sustainable and phased groundwater management strategy incorporating Managed Aquifer Recharge (MAR), seawater intrusion control, and demand-side management.
8. **To optimise MAR interventions through material–structure integration:** Identify suitable materials (e.g., filter media, geotextiles, low-permeability barriers) to enhance the efficiency, durability, and performance of proposed recharge structures.

4.3 Scope of the Study

The scope of the present study is defined as follows:

1. **Spatial Scope:** The study is confined to **Khadir Island (~315 km²)** located within the Great Rann of Kachchh, Gujarat, India.
2. **Temporal Scope:** The analysis covers the period **2001–2023**, integrating long-term historical datasets with field investigations conducted during the **post-monsoon seasons of 2019 and 2021**.
3. **Hydrogeological Characterisation:** Evaluation of geological, lithological, geomorphological, and hydrogeological conditions influencing groundwater occurrence and movement.
4. **Groundwater Potential Assessment:** Delineation of groundwater potential zones using **Remote Sensing (RS) and GIS-based Multi-Influencing Factor (MIF) analysis**.
5. **Groundwater Flow Modelling:** Development of a **transient three-dimensional groundwater flow model** using MODFLOW-6 to simulate aquifer dynamics.
6. **Seawater Intrusion Analysis:** Simulation and assessment of seawater intrusion processes using the **SWI2 package**, including spatial and temporal progression.
7. **Hydrochemical Evaluation:** Analysis of groundwater quality using hydrochemical parameters to validate model outputs and identify salinity sources.
8. **Water Demand Assessment:** Estimation of sector-wise water demand, including **domestic, agricultural, livestock, and tourism sectors**.
9. **Water Stress Analysis:** Evaluation of supply–demand relationships and assessment of groundwater stress using indicators such as the **Water Stress Index (WSI)**.

10. **Integrated Water Resource Planning:** Formulation of a **phased (2026–2035) water resource development plan**, incorporating:

- Managed Aquifer Recharge (MAR) structures
- Seawater intrusion control measures
- Demand-side management strategies

11. **Material–Structure Integration in MAR:** Incorporation of **site-specific material selection (filter media, geotextiles, low-permeability barriers)** to enhance the efficiency and sustainability of recharge interventions.

5. ORIGINAL CONTRIBUTIONS OF THE THESIS

The major novelty of this thesis lies in integrating hydrogeological modelling with material-optimized MAR design to develop a practical and scalable groundwater management framework for arid island systems. The present study makes the following original contributions to the field of hydrogeology and sustainable water resource management in arid island environments:

1. **First systematic groundwater potential zonation for a GRK island:** Development of a **Groundwater Potential Zone (GWPZ) map** for Khadir Island using an integrated **RS–GIS-based Multi-Influencing Factor (MIF) approach**, validated with field-based hydrochemical data (TDS ranging from 250 mg/L to ~7,200 mg/L), demonstrating strong agreement between spatial potential and groundwater quality.
2. **Integrated groundwater flow and seawater intrusion modelling framework:** Establishment of the **first coupled modelling framework for Khadir Island** using **MODFLOW-6 and SWI2**, enabling quantitative evaluation of groundwater dynamics and saline intrusion processes under data-scarce conditions.
3. **Quantification of groundwater budget and system behaviour:** Determination of the groundwater balance, showing that recharge ($\sim 2.45 \times 10^7 \text{ m}^3/\text{year}$) is largely offset by evapotranspiration (48.2%) and coastal outflow (45.7%), indicating a **recharge-rich but availability-limited system**.
4. **First long-term assessment of seawater intrusion dynamics (2001–2025):** Quantification of intrusion progression from ~1 km (2005) to ~6.3 km (2020) and ~7.2 km (2025), with intrusion rates of 0.20–0.48 km/year, and identification of a **critical threshold (~2.4 km)** beyond which rapid inland migration occurs.
5. **Development of a multi-line validation framework for data-scarce regions:** Integration of **water balance closure (<0.5% error)**, **sensitivity analysis**,

hydrochemical indicators ($\text{Na}^+/\text{Cl}^- < 0.86$), and field observations, enhancing the reliability of modelling outcomes in limited data environments.

6. **Comprehensive water demand and stress assessment framework:** Integrated evaluation of sector-wise water demand (domestic, agriculture, livestock, tourism) and groundwater availability, revealing stable demand (~290–293 MCM) and **intermittent critical stress conditions (WSI: 0.65–1.05)** driven by recharge variability.
7. **Material–structure integrated MAR design approach:** Introduction of a **novel material-informed approach** linking hydrogeological suitability with appropriate materials (graded filter media, geotextiles, clay cores, geomembranes) to improve the efficiency, durability, and performance of **Managed Aquifer Recharge (MAR) structures** under saline and arid conditions.
8. **Development of a phased integrated water resource management plan (2026–2035):** Formulation of a **10-year, five-phase implementation strategy** combining demand reduction (~27%), supply enhancement (~90 MLY through 23 MAR structures), seawater intrusion control, palaeochannel exploration, and community-based governance.
9. **Replicable framework for arid island hydrogeology:** Establishment of a **holistic and transferable geo-hydrological framework** that integrates RS–GIS, numerical modelling, hydrochemistry, and planning, providing a model for sustainable groundwater management in similar arid and coastal island environments.

6. METHODOLOGY OF RESEARCH, RESULTS / COMPARISONS

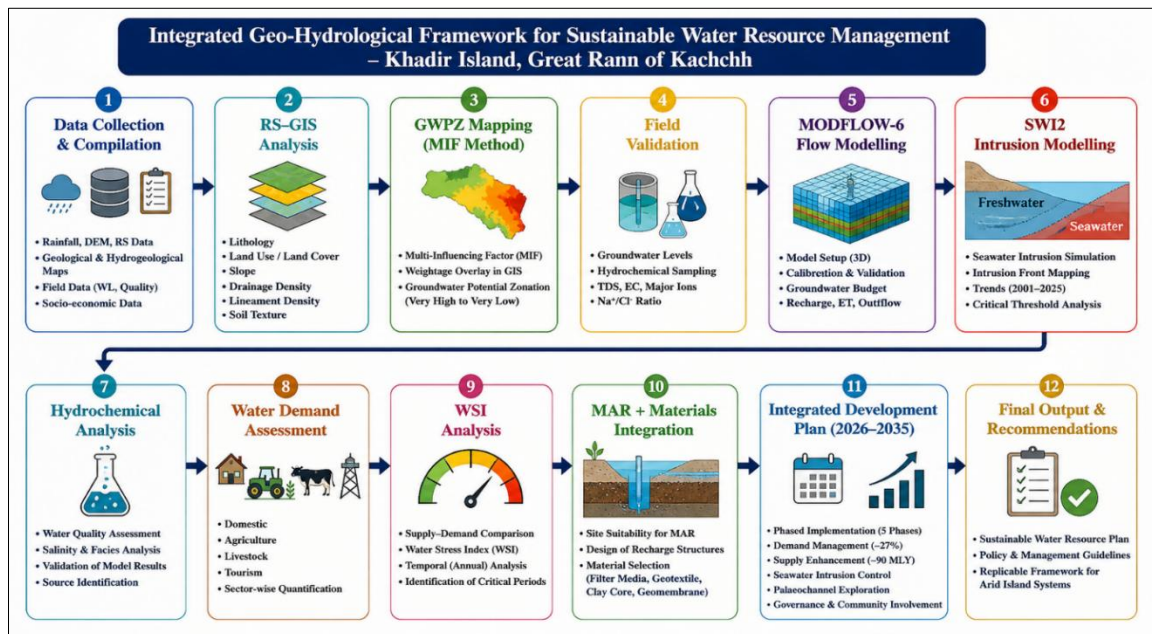


Figure 3: Methodological Flow chart of the Study

The study follows an integrated geo-hydrological framework combining field data, RS–GIS analysis, and groundwater potential mapping to understand aquifer characteristics. Numerical modelling using MODFLOW-6 and SWI2 is employed to simulate groundwater flow and seawater intrusion dynamics. These results are validated through hydrochemical analysis and linked with sector-wise water demand and stress assessment using WSI. Finally, the outcomes are synthesized into a material-informed MAR strategy and a phased integrated water resource development plan for sustainable management.

6.1 Field Investigation

Table 1: Field Water Quality Data (2019 & 2021)

Well ID	Village	TDS 2019 (mg/L)	TDS 2021 (mg/L)	Key Observations
KW-01	Ratanpar	2581	2450	Two fault planes nearby
KW-02	Janan	1550	1480	Igneous rock at 450 ft
KW-03	Janan	1200	1180	Highly weathered sandstone
KW-04	Dholavira	260	250	Downstream of reservoir; lowest TDS
KW-05	Dholavira	1800	1750	Brackish up to 200 ft
KW-06	Natural spring	4900	4850	Highest TDS; shale intercalation
KW-07	Near check dam	2700	2650	Fossiliferous limestone
KW-08	Near check dam	1975	1900	Good quality below 200 ft

Two systematic field campaigns were conducted during **post-monsoon 2019 and 2021**. Eight representative wells (KW-01 to KW-08) were inventoried across Ratanpar, Janan, Dholavira, and areas near check dams and a natural spring. For each well, UTM coordinates (GPS, ± 3 m), pH, TDS, temperature, well depth, motor depth, lithology, structural features, and cropping pattern were recorded.

Long-term Government Monitoring Well Data (KC-13 & HP11_KCH_006):

Year	Well	Water Level (m bgl)	TDS (mg/L)	Cl ⁻ (mg/L)	Status
1995	KC-13	5.95	1,220	120	Good quality
2005	KC-13	7.93	4,555	2,340	TDS increased sharply
2010	KC-13	7.80	8,875	4,760	Very high salinity
2015	KC-13	Dry	Dry	Dry	Well completely dry
2020	KC-13	10.20	2,720	1,000	Recovered
2015	HP11_KCH_006	7.65	7,170	4,140	High salinity
2020	HP11_KCH_006	7.28	7,250	4,300	Persistent high salinity

Key field findings: Sandstone formations yield better water quality; shale acts as semi-confining layer; igneous basement at 450 ft; fault planes control localized salinity. Cropping pattern: bajra, jeera, fruits, vegetables (uniform across villages).

6.2 RS-GIS-MIF for GWPZ and MAR Siting

Groundwater potential zonation for Khadir Island was carried out using an **RS–GIS-based Multi-Influencing Factor (MIF) approach**, integrating eight thematic layers: lithology, geomorphology, lineament density, rainfall, slope, drainage density, land use/land cover (LULC), and soil type. These layers were derived from **Landsat 8 OLI (30 m)**, **Sentinel-2 MSI (10 m)**, **SRTM DEM (30 m)**, and **Cartosat-1 (2.5 m)** datasets.

The relative influence of each factor was quantified through MIF weighting, with **drainage density (22.6%)** and **LULC (19.4%)** exerting the highest control, followed by geomorphology, lineament density, and soil type (each 16.1%), slope (12.9%), lithology (9.7%), and rainfall (6.5%).

6.2.1 GWPZ Classification

The resulting GWPZ map delineates three groundwater potential zones:

- **Good Zone:** 26.65 km² (8.45%) — primarily in Ratanpar, Janan, and western Dholavira
- **Moderate Zone:** 285.10 km² (90.45%) — covering most central and eastern parts
- **Poor Zone:** 3.45 km² (1.10%) — mainly Kalyanpar and Gadhada

A clear **west–east gradient** is observed, where groundwater potential decreases towards the east. This spatial pattern is consistent with:

- Coarser lithology (sandstone/limestone) in the west versus shale in the east
- Higher lineament density and lower drainage density in the west
- Coarser soils and better infiltration conditions
- Supporting hydrochemical evidence

6.2.2 Validation with Field Data

The GWPZ results were validated using field hydrochemical data:

- **KW-04 (Good zone):** TDS ~250 mg/L
- **KW-02/03 (Moderate zone):** TDS 1,180–1,550 mg/L
- **HPII_KCH_006 (Poor zone):** TDS ~7,200 mg/L

Additionally, long-term monitoring wells show a clear contrast: Dholavira (Good zone) exhibits recovery and relatively lower salinity, whereas Kalyanpar (Poor zone) shows persistently high TDS with clear seawater intrusion signatures. This confirms the **strong agreement between GWPZ classification and groundwater quality**.

6.2.3 Implications for Water Resource Development

The GWPZ map provides a robust basis for targeted groundwater management:

- **Good zones (8.45%):** Prioritised for high-yield wells and recharge enhancement → **8 recharge shafts + 6 percolation tanks proposed**
- **Moderate zones (90.45%):** Suitable for domestic supply and controlled irrigation → Additional MAR structures recommended
- **Poor zones (1.10%):** Unsuitable for shallow groundwater development → **Deep recharge shaft (Gadhada) + bandharas for intrusion control**

6.2.4 MAR Planning

A total of **23 Managed Aquifer Recharge (MAR) structures** are proposed:

- **7 Recharge shafts**
- **6 Percolation tanks**
- **5 Check dams**
- **5 Bandharas**

Among these, **bandharas play a critical role** in coastal zones by reducing tidal ingress and mitigating seawater intrusion, thereby protecting the freshwater lens.

6.3 GROUNDWATER FLOW MODELLING (MODFLOW-6)

A transient groundwater flow model was developed for the period **2001–2020** using ModelMuse 4.4.3. The model domain represents Khadir Island and was discretised into a **107 × 58 finite-difference grid with 300 m resolution**, comprising **four hydrostratigraphic layers** consistent with the geological framework described. Temporal discretisation included **80 quarterly stress periods**, enabling representation of seasonal variability in recharge, abstraction, and evapotranspiration.

5.3.1 Boundary Conditions and Inputs:

The model incorporates the following key processes:

- **Recharge (RCH):** 8.5% of mean annual rainfall (~378 mm)
- **Evapotranspiration (EVT):** 5.6 mm/day
- **Abstraction (WEL):** ~1.257 MCM/year (distributed across irrigation, domestic, and livestock uses)
- **Boundary conditions:** CHD (eastern boundary), GHB (coastal margins), RIV (ephemeral drainage)

6.3.2 Model Calibration:

Calibration was performed against observed groundwater levels from:

- **KC-13 (Dholavira)**
- **HPII_KCH_006 (Kalyanpar)**

The model achieved strong agreement with observed data:

- **RMSE:** 1.24 m
- **MAE:** 0.98 m
- **Mass balance error:** <0.5%

These results confirm the reliability of the model for simulating regional groundwater dynamics.

6.3.3 Groundwater Budget (2001–2020):

The zone budget analysis indicates that **recharge ($\sim 2.45 \times 10^7 \text{ m}^3/\text{year}$)** is the sole inflow component, while outflows are distributed as:

- **Evapotranspiration:** 48.2%
- **Coastal outflow:** 45.7%
- **Groundwater abstraction:** ~5.1%
- **Storage change:** -0.3% (negligible)

Although recharge appears substantial, the system is effectively **availability-limited**, as most inflow is lost through evapotranspiration and lateral discharge to the surrounding Rann.

This behaviour indicates a **near steady-state condition**, where groundwater storage remains relatively stable over time.

Importantly, despite representing a small fraction of the total budget, abstraction significantly influences the **hydraulic gradient**, thereby playing a critical role in controlling seawater intrusion dynamics.

The calibrated model demonstrates high reliability for regional-scale simulation under data-scarce conditions

6.4 SEAWATER INTRUSION MODELLING (MODFLOW-SWI2)

Seawater intrusion in the coastal aquifer of Khadir Island was simulated using the **SWI2 package of MODFLOW-6**, which applies a density-dependent sharp interface approach to represent the freshwater–saltwater system. Freshwater (1000 kg/m^3) and seawater (1025 kg/m^3) are treated as immiscible fluids separated by a movable interface, making the method suitable for data-scarce island conditions.

The SWI2 model was developed based on the calibrated groundwater flow model (Section 7.3), with consistent boundary conditions, recharge, evapotranspiration, and abstraction ($\sim 5 \text{ L/s}$). Simulations were carried out for **2001–2020**, with interpretation extended to **2025** based on model trends and field evidence.

6.4.1 Intrusion Progression

The results indicate a continuous inland migration of the saline interface:

- **2005:** $\sim 1.0 \text{ km}$
- **2010:** $\sim 2.4 \text{ km}$ (critical threshold)
- **2015:** $\sim 3.9 \text{ km}$
- **2020:** $\sim 6.3 \text{ km}$
- **2025:** $\sim 7.2 \text{ km}$ (advanced stage)

6.4.2 Intrusion Rates

- **2005–2010:** $\sim 0.20 \text{ km/year}$
- **2010–2015:** $\sim 0.30 \text{ km/year}$
- **2015–2020:** $\sim 0.48 \text{ km/year}$
- **2020–2025:** $\sim 0.18 \text{ km/year}$

The reduced rate after 2020 reflects hydraulic constraints rather than recovery, with the system remaining under stress.

6.4.3 Critical Threshold and Validation

A critical threshold is identified at **~2.4 km (2010)**, beyond which intrusion accelerates due to reduced freshwater gradients. Hydrochemical evidence supports the model, with $\text{Na}^+/\text{Cl}^- < 0.86$ indicating marine origin and absence of $\text{NO}_3^-/\text{PO}_4^{3-}$ ruling out anthropogenic sources.

Current Status (2025)

By 2025, intrusion has advanced to **~7.2 km**, indicating an **advanced stage of seawater intrusion**. This significantly limits freshwater availability and highlights the need for immediate management interventions such as recharge enhancement and abstraction control.

6.5 Water Demand, Availability and Stress Assessment

The assessment of groundwater stress in Khadir Island was carried out by integrating sector-wise water demand estimation with observed groundwater availability and future projections. The analysis captures the temporal dynamics between demand and supply under highly variable climatic conditions.

6.5.1 Water Demand Assessment (2001–2041)

Total water demand was estimated by integrating **domestic, livestock, tourism, and agricultural sectors** using standard guidelines: CPHEEO (domestic: 135 LPCD), FAO (livestock), FAO-56 (crop water requirement), and the equivalent population method (tourism).

The total water demand shows **remarkable stability over the study period**, increasing marginally from **290.97 MCM in 2001 to 292.65 MCM in 2041**. This stability is primarily due to the dominance of agriculture, which accounts for **more than 99% of total water demand** (Allen et al., 1998).

While domestic, livestock, and tourism demands exhibit gradual increases due to population growth and tourism development, their contribution remains negligible compared to agricultural demand.

6.5.2 Water Availability Analysis (2011–2025)

Groundwater availability was estimated based on **post-monsoon recharge and observed water levels**, representing the usable water after accounting for natural losses.

The results indicate **high interannual variability in water availability**, ranging from:

- **Minimum:** ~1,256 MLY (dry years)
- **Maximum:** ~2,324 MLY (wet years)
- **Average:** ~1,790.63 MLY

This variability is strongly controlled by **monsoon rainfall fluctuations**, leading to alternating surplus and deficit conditions.

Although **surplus conditions dominate most years**, **deficit conditions were observed in 2018 and 2024**, indicating vulnerability during low rainfall periods.

6.5.3 Supply–Demand Relationship

A comparison of water availability and demand reveals a critical system behaviour:

- **Recharge ($2.45 \times 10^7 \text{ m}^3/\text{year} \approx 24,500 \text{ MLY}$)** is significantly higher than demand ($\sim 292 \text{ MLY}$)
- However, only **$\sim 5\text{--}9\%$ of recharge is effectively available for use**, due to:
 - Evapotranspiration ($\sim 48.2\%$)
 - Lateral outflow to the coast ($\sim 45.7\%$)

Thus, despite being **recharge-rich**, the system is effectively **availability-limited**.

Water demand constitutes approximately **12–25% of available water**, indicating overall adequacy under normal conditions, but **sensitivity to rainfall variability**.

6.5.4 Water Stress Index (WSI) Analysis (2026–2030)

The **Water Stress Index (WSI)** is defined as the ratio of total water demand to total water availability and is used to assess the level of stress on groundwater resources. The projected results indicate:

- **WSI range:** 0.65 to 1.05
- **Moderate stress conditions** in most years
- **Critical stress in 2028 (WSI = 1.05)**

This highlights the occurrence of **intermittent water stress**, driven primarily by fluctuations in recharge rather than demand growth.

6.5.5 Key Interpretation

The integrated analysis reveals that:

- Water demand in Khadir Island remains **nearly constant and agriculture-dominated**
- Groundwater availability is **highly variable and rainfall-dependent**
- The system experiences **episodic deficits despite overall surplus conditions**
- Future projections indicate **intermittent critical stress**, particularly under low recharge scenarios

6.5.6 Implications for Water Management

The findings emphasize that sustainable water management in Khadir Island requires:

- **Enhancement of groundwater recharge** through MAR and watershed interventions
- **Reduction of evapotranspiration losses** via land and irrigation management
- **Efficient irrigation practices** to control dominant agricultural demand
- **Adaptive groundwater governance** to manage variability and prevent over-extraction

Although Khadir Island is **hydrologically recharge-rich**, its groundwater system is **availability-constrained due to significant natural losses and climatic variability**, leading to **intermittent water stress conditions**. This underscores the need for an **integrated demand–supply management framework** to ensure long-term water security.

6.6 Integrated Water Resource Development Plan (2026–2035)

Based on the hydrogeological assessment, numerical modelling (MODFLOW–SWI2), groundwater potential zonation, and demand–supply analysis, a 10-year phased integrated water resource development plan has been formulated for Khadir Island. The plan addresses groundwater depletion, seawater intrusion, and demand inefficiencies through a combination of technical interventions, Managed Aquifer Recharge (MAR), and community-based governance mechanisms.

6.6.1 Planning Framework and Approach

The development strategy follows a phased and adaptive framework, integrating:

- Demand-side management (efficiency improvement and abstraction control)
- Supply-side enhancement through Managed Aquifer Recharge (MAR)
- Seawater intrusion mitigation
- Exploration of alternative freshwater sources
- Community participation and institutional strengthening

The adoption of MAR as a central component is supported by its proven effectiveness in enhancing recharge and improving groundwater sustainability in arid and semi-arid regions (Dillon et al., 2020; Bouwer, 2002). Similarly, coastal aquifer management requires integration of recharge and intrusion control measures to maintain hydraulic balance (Werner et al., 2013). In addition, the plan incorporates a material–structure integration approach, ensuring that each recharge intervention is supported by suitable materials to improve infiltration efficiency, reduce clogging, and enhance durability under saline conditions (Bouwer, 2002; CGWB, 2007).

In arid and saline hydrogeological environments, the long-term performance of Managed Aquifer Recharge (MAR) systems is strongly influenced by material characteristics such as permeability, filtration capacity, erosion resistance, and clogging behaviour. Therefore,

suitable materials including graded filter media, geotextiles, clay barriers, riprap, and geomembranes are integrated with recharge structure design to improve recharge efficiency, reduce maintenance requirements, and enhance structural durability under saline conditions

6.6.2 Phase-wise Implementation Strategy

Phase 1 (2026–2027): Emergency Demand Management and Monitoring

This initial phase focuses on stabilizing the groundwater system through:

- Water conservation and awareness programs
- Installation of flow meters and regulation of new wells
- Strengthening monitoring networks
- Formation of Village Water User Associations (VWUAs)

Improved monitoring and abstraction control are essential for sustainable groundwater management in stressed aquifers (Famiglietti, 2014).

Phase 2 (2027–2029): Agricultural Efficiency and MAR Implementation

This phase targets the dominant water-consuming sector (agriculture):

- Adoption of efficient irrigation systems (e.g., drip irrigation)
- Construction of check dams, recharge shafts, and percolation tanks
- Canal lining to reduce conveyance losses
- Implementation of pilot-scale MAR interventions

Artificial recharge structures such as recharge shafts and percolation tanks have been widely used in India for enhancing groundwater recharge (CGWB, 2007). Their performance can be improved through proper design and material selection to prevent clogging and maintain infiltration capacity (Bouwer, 2002).

Phase 3 (2028–2030): Seawater Intrusion Control

This phase focuses on mitigating saline ingress:

- Construction of bandharas (subsurface barriers)
- Establishment of abstraction caps in critical zones
- Implementation of regulatory mechanisms

Subsurface barriers are effective in controlling seawater intrusion by maintaining freshwater heads and limiting inland saline movement (Bear et al., 1999; Werner et al., 2013).

Phase 4 (2029–2032): Palaeochannel Exploration and Alternative Sources

This phase explores additional freshwater potential:

- Identification of palaeochannels through exploratory boreholes
- Development of deep recharge systems

- Evaluation of desalination options (if required)
- Brine management planning

Exploration of palaeochannels has been shown to enhance groundwater availability in arid environments due to their higher permeability and storage capacity.

Phase 5 (2030–2035): Livelihood Integration and Sustainability

This phase ensures long-term sustainability:

- Promotion of traditional practices (e.g., Piloodi cultivation)
- Development of alternative livelihoods (tourism)
- Establishment of a water fund
- Periodic review and adaptive management

Community participation plays a crucial role in the long-term success of groundwater management strategies (Dillon et al., 2020).

6.6.3 Intervention Summary and Expected Outcomes:

A total of 23 MAR and control structures are proposed:

- 5 check dams
- 7 recharge shafts
- 6 percolation tanks
- 5 bandharas

These interventions aim to:

- Enhance groundwater recharge and storage
- Reduce runoff and improve soil moisture
- Control seawater intrusion and protect freshwater zones
- Provide supplementary water supply where required

The integrated system is expected to generate approximately ~90 MLY of additional usable water, contributing significantly to water security.

6.6.4 Key Outcomes:

The implementation of this plan is expected to achieve:

- Improved groundwater availability and quality
- Reduction in seawater intrusion impacts
- Enhanced agricultural sustainability through efficient irrigation practices (Allen et al., 1998)
- Diversified livelihoods and reduced dependence on groundwater
- Strengthened community-based governance
- Long-term resilience through monitoring and adaptive management

6.6.5 Final Perspective:

The proposed phased plan translates scientific findings into a practical and implementable roadmap for Khadir Island. Despite being recharge-rich, the aquifer system is availability-limited due to high evapotranspiration and coastal outflow losses, necessitating integrated management.

By combining recharge enhancement, demand regulation, intrusion control, and institutional mechanisms, the plan provides a sustainable pathway for groundwater management. The framework is replicable for other arid island systems of the Great Rann of Kachchh and similar coastal environments worldwide.

7. CONCLUSION

This thesis demonstrates that an integrated geo-hydrological framework—combining RS–GIS-based MIF analysis, numerical modelling (MODFLOW-6 and SWI2), systematic field investigations, hydrochemistry, water demand assessment, and participatory planning—provides a robust approach to diagnose groundwater stress and develop sustainable management strategies for arid island environments such as Khadir Island. The study further advances this framework by incorporating material–structure integration within Managed Aquifer Recharge (MAR) systems to improve efficiency, durability, and resilience under saline and arid conditions.

7.1 Key Hydrogeological Findings

Field investigations and modelling results indicate that groundwater conditions in Khadir Island are severely stressed and spatially heterogeneous:

- Groundwater quality shows significant variation, with TDS ranging from 250 mg/L (recharge zones) to ~7,200 mg/L (intrusion-affected zones).
- Lithology and structural controls strongly influence groundwater occurrence and quality, with sandstone units yielding relatively fresh water, while shale formations and fault-controlled zones promote salinity.
- Long-term monitoring indicates partial aquifer recovery in recharge zones (Dholavira), whereas persistent seawater intrusion is evident in Kalyanpar, confirmed by Na^+/Cl^- ratios <0.86 .
- Although groundwater abstraction (~1,257 MLY) represents a relatively small fraction of the overall groundwater budget, localized over-extraction significantly alters hydraulic gradients and accelerates seawater intrusion in vulnerable coastal zones. Therefore, a 30–40% reduction in abstraction is recommended in critical areas.

Groundwater System Behaviour and Seawater Intrusion

The integrated modelling framework provides key insights into aquifer dynamics:

- The groundwater system is recharge-driven but availability-limited, with recharge ($\sim 2.45 \times 10^7 \text{ m}^3/\text{year}$) largely lost through evapotranspiration (48.2%) and coastal outflow (45.7%).
- Seawater intrusion has progressed from $\sim 1 \text{ km}$ (2005) to $\sim 6.3 \text{ km}$ (2020) and $\sim 7.2 \text{ km}$ (2025).
- Intrusion rates range from 0.20–0.48 km/year, with a reduced rate ($\sim 0.18 \text{ km/year}$ during 2020–2025), indicating an advanced stage of intrusion.
- A critical threshold at $\sim 2.4 \text{ km}$ is identified, beyond which intrusion accelerates significantly.

7.3 Water Demand and Stress Dynamics

The demand–supply analysis highlights a critical imbalance driven by variability:

- Total water demand remains nearly constant ($\sim 290\text{--}293 \text{ MCM}$) over 2001–2041, with agriculture contributing $>99\%$.
- Groundwater availability exhibits high interannual variability (1,256–2,324 MLY), primarily controlled by rainfall fluctuations.
- Despite high recharge, only $\sim 5\text{--}9\%$ is effectively available, making the system availability-constrained.
- Future projections (2026–2030) indicate WSI values of 0.65–1.05, reflecting intermittent critical water stress, particularly during low recharge years (Falkenmark et al., 1989).

7.4 Methodological and Scientific Contributions

This study makes several original contributions to hydrogeology and water resource management:

- First systematic GWPZ mapping for a GRK island using RS–GIS-based MIF, validated with hydrochemical data, demonstrating strong agreement between groundwater potential and quality.
- First integrated MODFLOW-6 and SWI2 modelling framework for Khadir Island, enabling quantification of groundwater budget and seawater intrusion dynamics.
- First long-term quantification of seawater intrusion (2001–2025) for GRK islands, establishing a benchmark for arid coastal aquifers.
- Development of a multi-line validation framework for data-scarce regions, integrating water balance closure ($<0.5\%$), sensitivity analysis, hydrochemical indicators, and field observations.

- Integration of material–structure design within MAR systems, linking hydrogeological suitability with appropriate materials (filter media, geotextiles, clay cores, geomembranes) to enhance recharge efficiency, reduce clogging, and improve structural durability.
- Comprehensive demand–supply and water stress assessment framework, linking hydrogeological processes with socio-economic drivers.

7.5 Management Implications and Way Forward

Based on the findings, a 10-year, five-phase integrated water resource development plan (2026–2035) is proposed:

- Demand reduction (~27%) through efficient irrigation and water-use practices
- Supply enhancement (~90 MLY) via 23 Managed Aquifer Recharge (MAR) structures
- Seawater intrusion mitigation through bandharas and abstraction control
- Palaeochannel exploration for additional groundwater resources
- Material–structure optimization to improve performance and longevity of MAR systems
- Community-based governance frameworks (VWUAs, KIWRC) with monitoring and adaptive management

7.6 Final Synthesis

The study establishes that the Khadir Island aquifer has reached an advanced critical stage of seawater intrusion (~7.2 km by 2025) and represents a recharge-rich but availability-limited system.

By integrating hydrogeological analysis, numerical modelling, MAR design, and material optimization, the study provides a scientifically robust and practically implementable framework for groundwater management.

An integrated, science-based, and community-driven approach can enable the transition from groundwater crisis to sustainable water security, offering a replicable model for other arid island systems in the Great Rann of Kachchh and similar environments globally.

8. FUTURE SCOPE AND RECOMMENDATION:

Future work may incorporate climate change scenarios to assess long-term impacts on groundwater recharge and seawater intrusion. Advanced density-dependent modelling and isotopic techniques can improve understanding of freshwater–saline interactions and recharge sources. Strengthening monitoring networks and optimizing material-based MAR designs will enhance system reliability. The developed framework can be extended to other islands of the Great Rann of Kachchh for regional water resource management.

9. PATENT

NA

10. LIST OF ALL PUBLICATIONS ARISING FROM THE THESIS

Research Paper Title	Name of Journal	ISSN No.	Listed in (UGC Care/ Scopus/ WoS/ Other)	Website Link
Fluid Dynamics of a Stressed Freshwater Lens: Integrated Flow Modeling and Pathways for Material-Centric Interventions in Khadir Island, Gujarat	Journal of Polymer & Composites	2394-7799 (Print) 2394-7802 (Online)	Web of Science	https://doi.org/10.37591/JOPC.v14i02.238343
Integrated Water Balance and Water Stress Index–Based Sustainability Assessment of a Semi-Arid Island Ecosystem	Journal of Water Pollution & Purification Research	2394-7306	Other Peer Review	https://doi.org/10.37591/JoWPPR.v13i01.238470
Buried Rivers, Thirsty Island Belt: A Review of Water Challenges in the Great Rann of Kachchh	International Journal of Environmental Chemistry	2456-5245	Other Peer Review	https://doi.org/10.37628/ijec.v12i01.24655

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