

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

A Thesis submitted to Gujarat Technological University

for the Award of

Doctor of Philosophy

in

CIVIL ENGINEERING

by

NIMAVAT SAGAR VINODRAY

179999912013

Under supervision of

Dr. Mahendrasinh Shivraj Gadhavi

Asst. Prof. Civil Engineering Department

L. D. College of Engineering-Ahmedabad



GUJARAT TECHNOLOGICAL UNIVERSITY AHMEDABAD

[OCTOBER – 2026]

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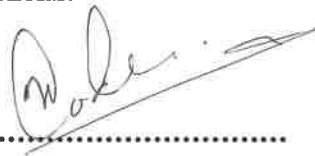
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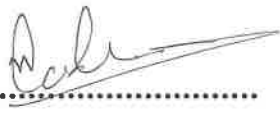
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LIST OF ABBREVIATIONS

Abbreviation	Full Form
AHP	Analytic Hierarchy Process
AMSL	Above Mean Sea Level
CGWB	Central Ground Water Board
CPHEEO	Central Public Health and Environmental Engineering Organisation
DEM	Digital Elevation Model
FAO	Food and Agriculture Organization
GIS	Geographic Information System
GSI	Geological Survey of India
GRK	Great Rann of Kachchh
GWPZ	Groundwater Potential Zone
GWRDC	Gujarat Water Resources Development Corporation
IMD	India Meteorological Department
IPCC	Intergovernmental Panel on Climate Change
ISRO	Indian Space Research Organisation
LPCD	Litres Per Capita per Day
LULC	Land Use / Land Cover
MAR	Managed Aquifer Recharge
MCDA	Multi-Criteria Decision Analysis
MCM	Million Cubic Metre
MIF	Multi-Influencing Factor
MLD	Million Litres per Day
MODFLOW	Modular Finite-Difference Groundwater Flow Model

Abbreviation	Full Form
NAFCC	National Adaptation Fund for Climate Change
NRSC	National Remote Sensing Centre
ONGC	Oil and Natural Gas Corporation
PHAST	PHAST Groundwater Simulation Program
RMS	Root Mean Square
RMSE	Root Mean Square Error
RS	Remote Sensing
SWI2	Saltwater Intrusion Package Version 2
TDS	Total Dissolved Solids
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
VWUA	Village Water User Association
WSI	Water Stress Index
WTF	Water Table Fluctuation

LIST OF SYMBOLS

Symbol	Description	Unit
K	Hydraulic conductivity	m/day
K _{xx}	Hydraulic conductivity in x-direction	m/day
K _{yy}	Hydraulic conductivity in y-direction	m/day
K _{zz}	Hydraulic conductivity in z-direction	m/day
h	Hydraulic head	m
S _s	Specific storage	1/m
S _y	Specific yield	dimensionless
q _s	Volumetric flux per unit volume	1/day
R	Groundwater recharge	mm/year
z	Interface depth below mean sea level	m
ρ _f	Density of freshwater	kg/m ³
ρ _s	Density of saline water	kg/m ³
TDS	Total Dissolved Solids	mg/L
Na ⁺	Sodium ion concentration	mg/L
Cl ⁻	Chloride ion concentration	mg/L
Mg ²⁺	Magnesium ion concentration	mg/L
NO ₃ ⁻	Nitrate ion concentration	mg/L
PO ₄ ³⁻	Phosphate ion concentration	mg/L
WSI	Water Stress Index	dimensionless
WEI	Water Exploitation Index	%
PET	Potential Evapotranspiration	mm/year
AET	Actual Evapotranspiration	mm/year
MCM	Million Cubic Metres	10 ⁶ m ³
MLY	Million Litres per Year	10 ⁶ L/year
MLD	Million Litres per Day	10 ⁶ L/day
LPCD	Litres Per Capita per Day	L/person/day
DEM	Digital Elevation Model	—
GIS	Geographic Information System	—
RS	Remote Sensing	—
MIF	Multi-Influencing Factor	—

Symbol	Description	Unit
GWPZ	Groundwater Potential Zone	—
MAR	Managed Aquifer Recharge	—
LULC	Land Use/Land Cover	—
SRTM	Shuttle Radar Topography Mission	—
WTF	Water Table Fluctuation	—
RMSE	Root Mean Square Error	m
MAE	Mean Absolute Error	m
CV	Coefficient of Variation	%
m bgl	Metres below ground level	m
m amsl	Metres above mean sea level	m

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ABSTRACT

The Great Rann of Kachchh (GRK), India, is a hyper-arid salt desert with isolated inhabited islands (bets) dependent solely on groundwater. Khadir Island (~315 km², ~17,000 people, ten villages, UNESCO site Dholavira) faces acute water scarcity due to aquifer salinity, over-extraction, and seawater intrusion. This study develops an integrated geo-hydrological framework combining remote sensing, GIS, multi-criteria decision analysis, numerical modelling (MODFLOW-6, SWI2), hydrogeochemical validation, and socio-economic assessment.

Groundwater Potential Zones (GWPZ) were delineated using the Multi-Influencing Factor (MIF) method with eight thematic layers. Drainage density (22.6%) and LULC (19.4%) were the highest-weighted factors. The island was classified into Good (8.45%), Moderate (90.45%), and Poor (1.10%) zones, validated by hydrochemical data showing the Poor zone has 66% higher TDS and 330% higher chloride than the Good zone.

A transient MODFLOW-6 model (2001–2020, RMSE 1.24 m, mass balance error <0.5%) showed recharge (2.45×10^7 m³) balanced by evapotranspiration (48.2%) and coastal outflow (45.7%), with abstraction only 6.5%. Despite this, abstraction exceeds sustainable yield due to recharge variability (CV=61%), required coastal outflow, and seasonal mismatch. SWI2 modelling revealed seawater intrusion advanced from 0 to 6.3 km inland by 2020, accelerating from 0.20 to 0.48 km/yr, with a critical threshold at 2.4 km (2010). Projections indicate 7.95–9.60 km intrusion by 2025 without intervention.

A Managed Aquifer Recharge (MAR) strategy with 23 structures (7 recharge shafts, 6 percolation tanks, 5 check dams, 5 bandharas) was proposed. Water demand (2001–2041) is dominated by agriculture (>99%), with total demand reaching 292.65 MCM by 2041. Water Stress Index for 2026–2030 ranges from 0.65 (moderate) to 1.05 (critical), highlighting drought vulnerability. A five-phase, 10-year Integrated Water Resource Development Plan (2026–2035) targets 27% demand reduction and 60 MLY additional supply via MAR.

This study provides the first integrated geo-hydrological assessment and management framework for Khadir Island and the isolated bets of the GRK. Its principal scientific contribution lies in coupling RS-GIS-MIF groundwater potential mapping, transient MODFLOW-6 flow modelling, SWI2 seawater intrusion simulation, and hydrogeochemical validation to quantify the recharge–abstraction–intrusion nexus and identify a critical intrusion

threshold for timely intervention in a data-scarce, hyper-arid island aquifer. Practically, the findings translate into a phased, community-centred water resource development plan that integrates managed aquifer recharge, demand-side efficiency, and salinity-control measures, offering a replicable blueprint for sustainable water security in similar arid island and coastal aquifer systems globally.

Keywords: Groundwater potential zoning, Managed Aquifer Recharge, Seawater intrusion, MODFLOW, SWI2, Khadir Island, Great Rann of Kachchh, Remote sensing, GIS, MIF, Water Stress Index, Hydro geochemistry

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DEDICATION

My Study Work

Dedicated to

Shree Kamala Devi Mataji

(Our Divine Kuldevi)

Narayan Sarovar, Koteswar, Kutch

With deepest devotion and gratitude for her divine blessings, guidance, and protection
throughout my life and academic journey.

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
AHP	Analytic Hierarchy Process
AMSL	Above Mean Sea Level
CGWB	Central Ground Water Board
CPHEEO	Central Public Health and Environmental Engineering Organisation
DEM	Digital Elevation Model
FAO	Food and Agriculture Organization
GIS	Geographic Information System
GSI	Geological Survey of India
GRK	Great Rann of Kachchh
GWPZ	Groundwater Potential Zone
GWRDC	Gujarat Water Resources Development Corporation
IMD	India Meteorological Department
IPCC	Intergovernmental Panel on Climate Change
ISRO	Indian Space Research Organisation
LPCD	Litres Per Capita per Day
LULC	Land Use / Land Cover
MAR	Managed Aquifer Recharge
MCDA	Multi-Criteria Decision Analysis
MCM	Million Cubic Metre
MIF	Multi-Influencing Factor
MLD	Million Litres per Day
MODFLOW	Modular Finite-Difference Groundwater Flow Model

Abbreviation	Full Form
NAFCC	National Adaptation Fund for Climate Change
NRSC	National Remote Sensing Centre
ONGC	Oil and Natural Gas Corporation
PHAST	PHAST Groundwater Simulation Program
RMS	Root Mean Square
RMSE	Root Mean Square Error
RS	Remote Sensing
SWI2	Saltwater Intrusion Package Version 2
TDS	Total Dissolved Solids
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
VWUA	Village Water User Association
WSI	Water Stress Index
WTF	Water Table Fluctuation

LIST OF SYMBOLS

Symbol	Description	Unit
K	Hydraulic conductivity	m/day
K _{xx}	Hydraulic conductivity in x-direction	m/day
K _{yy}	Hydraulic conductivity in y-direction	m/day
K _{zz}	Hydraulic conductivity in z-direction	m/day
h	Hydraulic head	m
S _s	Specific storage	1/m
S _y	Specific yield	dimensionless
q _s	Volumetric flux per unit volume	1/day
R	Groundwater recharge	mm/year
z	Interface depth below mean sea level	m
ρ _f	Density of freshwater	kg/m ³
ρ _s	Density of saline water	kg/m ³
TDS	Total Dissolved Solids	mg/L
Na ⁺	Sodium ion concentration	mg/L
Cl ⁻	Chloride ion concentration	mg/L
Mg ²⁺	Magnesium ion concentration	mg/L
NO ₃ ⁻	Nitrate ion concentration	mg/L
PO ₄ ³⁻	Phosphate ion concentration	mg/L
WSI	Water Stress Index	dimensionless
WEI	Water Exploitation Index	%
PET	Potential Evapotranspiration	mm/year
AET	Actual Evapotranspiration	mm/year
MCM	Million Cubic Metres	10 ⁶ m ³
MLY	Million Litres per Year	10 ⁶ L/year
MLD	Million Litres per Day	10 ⁶ L/day
LPCD	Litres Per Capita per Day	L/person/day
DEM	Digital Elevation Model	—
GIS	Geographic Information System	—
RS	Remote Sensing	—
MIF	Multi-Influencing Factor	—

Symbol	Description	Unit
GWPZ	Groundwater Potential Zone	—
MAR	Managed Aquifer Recharge	—
LULC	Land Use/Land Cover	—
SRTM	Shuttle Radar Topography Mission	—
WTF	Water Table Fluctuation	—
RMSE	Root Mean Square Error	m
MAE	Mean Absolute Error	m
CV	Coefficient of Variation	%
m bgl	Metres below ground level	m
m amsl	Metres above mean sea level	m

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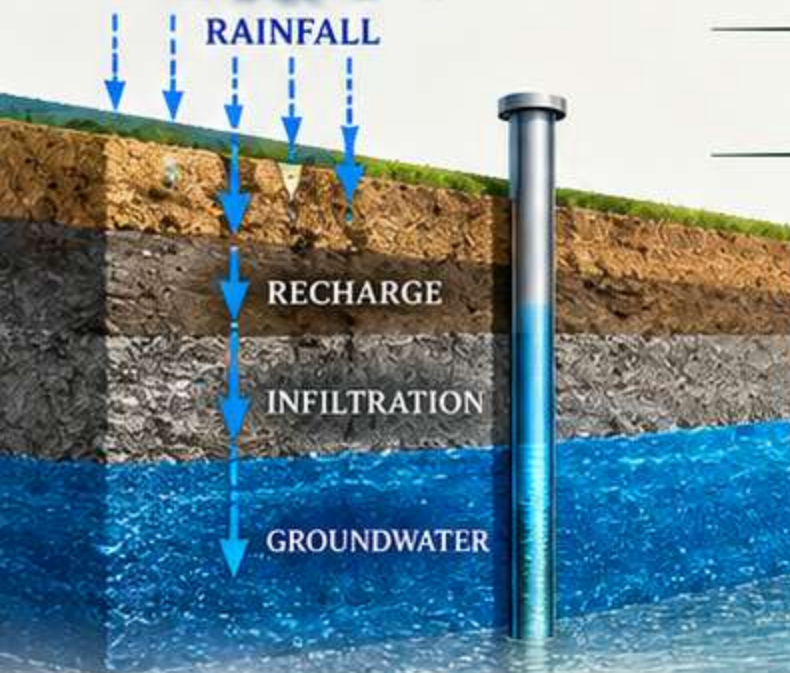
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GUJARAT TECHNOLOGICAL UNIVERSITY
AHMEDABAD



Chapter 1 – 9



WATER
RESOURCE



GEO-HYDROLOGICAL
APPROACH



ISOLATED
ISLANDS



HERITAGE
& CULTURE



SUSTAINABLE
DEVELOPMENT

"Setting the stage: why arid island water crises demand an integrated geo-hydrological response."

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1.1 Setting the Scene: The Global Groundwater Challenge

Groundwater is the world's most extracted raw material, and for good reason. In arid and semi-arid regions, where rivers run dry for most of the year and rainfall is both scarce and unpredictable, the water stored beneath our feet is often the only reliable source of freshwater. Across India, groundwater meets nearly 60% of the nation's irrigation needs and supplies more than 80% of rural drinking water (Freeze and Cherry, 1979; Scanlon et al., 2006; CGWB, 2023). This dependence, however, has come at a steep cost. In recent decades, unchecked pumping, climate variability, and land-use changes have pushed many aquifers into a state of chronic depletion and quality deterioration (Famiglietti, 2014).

Nowhere is this crisis more acute than in coastal and island aquifers. Here, the freshwater lens—a delicate, buoyant layer of fresh water floating over denser saline water—is highly vulnerable to seawater intrusion. Even a modest decline in the water table can trigger a rapid landward advance of the saltwater wedge, rendering wells unusable and threatening entire communities (Werner et al., 2013). Small islands in hyper-arid settings, with their thin lenses and negligible natural buffers, represent the extreme end of this vulnerability spectrum.

1.2 The Great Rann of Kachchh: A Salt Desert with Islands of Life

The Great Rann of Kachchh (GRK) in western Gujarat, India, is one of the most extraordinary and inhospitable landscapes on Earth. Covering more than 18,000 km², it is a vast, seasonal salt desert—a white expanse of cracked, saline mudflats that is flooded by the Arabian Sea during the monsoon and then bakes under a fierce sun for the rest of the year. The region has a subtropical climate characterised by extreme temperature variations. Summer temperatures routinely exceed 40°C and can reach as high as 50°C, while winter nights can see temperatures drop close to freezing (Britannica, 1998). The average annual rainfall is a meagre 380–420 mm, almost all of which falls during a brief, intense southwest monsoon from June to September (IMD, 2022). Potential evapotranspiration, at over 2,000 mm per year, far exceeds precipitation, creating a permanent atmospheric thirst that leaves the landscape parched for most of the year.

Scattered across the Great Rann of Kachchh are several elevated landmasses locally known as *bets* or islands, which remain above the seasonal inundation levels of the surrounding salt flats. These islands vary considerably in size, elevation, and geomorphological characteristics, ranging from relatively flat terrains to rugged uplands with prominent escarpments and steep northern slopes. Major islands include **Pachchham, Khadir, Bela, and**

Chorar, along with several smaller islands that support seasonal grazing and dispersed settlements. Among these, **Pachchham Island** is the largest and contains **Kalo Dungar (Black Hill)**, the highest peak in the Kachchh region, rising to approximately 462 m above mean sea level. **Khadir Island**, although smaller than Pachchham, is of exceptional archaeological, socio-economic, and hydrogeological significance owing to the presence of the UNESCO World Heritage Site of Dholavira and its dependence on limited freshwater resources. These elevated islands form distinct geomorphic units within the Great Rann and provide the only permanently habitable landscapes within an otherwise extensive saline environment.

What makes this region truly unique is not just its geology but its human story. For over 5,000 years, people have lived on these isolated islands. The most celebrated evidence of this ancient habitation is Dholavira, a UNESCO World Heritage Site and one of the largest and most well-preserved settlements of the Indus Valley (Harappan) civilization. The Harappans were master water managers, and the sophisticated water conservation systems they built at Dholavira—a network of reservoirs, channels, and bunds—stand as a testament to the timeless challenge of securing water in this unforgiving environment.

1.3 The People of the Rann: Population, Villages, and Livelihoods

The human geography of the GRK is as distinctive as its physical landscape. The permanent population is concentrated in the Banni grasslands, which lie on the southern fringe of the Rann, and on the bets themselves. The total population of the Banni region is estimated to be around 17,000 to 25,000 people, spread across approximately 48 to 58 hamlets that are organised into 19 panchayats (Maldhari Biocultural Protocol, 2011; Sahapedia, undated). Approximately 90% of the population is Muslim, comprising various pastoralist communities, while the remaining 10% are Hindu Meghwals and Vadha Kolis.

The pastoralist communities—known locally as *Maldhari*—are the heart of the region's economy and culture. They are organised into about 20 different clans, including the Halepotra, Raysipotra, Mutva, Jat, Hingorja, Node, Sumra, and Sameja. They speak a dialect of Kachchhi that is heavily influenced by Sindhi, reflecting their historical migration from the Sindh region of what is now Pakistan. The Maldharis are traditionally semi-nomadic pastoralists, moving with their herds across the Banni grasslands in response to the seasonal availability of water and fodder. Their livestock includes indigenous breeds remarkably well-adapted to the harsh conditions—the Banni buffalo, Kankrej cattle, Sindhi horse, Kachchhi goat, and Kachchhi camel (Sahapedia, undated). Milk and milk products, particularly from the highly prized Banni

buffalo, are their primary source of income. A detailed cross-sectional study of the Banni economy found that the sale of milk and milk products generated the highest average annual net income of approximately ₹414,070 per household, contributing as much as 82% to the region's total economy (India Water Portal, 2024).

The Hindu Meghwal and Vadha Koli communities, while also keeping some livestock, have a different traditional specialisation. They are renowned for their exquisite embroidery, leatherwork, wood-carving, and the construction of *bhungas*—the traditional circular mud houses with intricately decorated interiors that are emblematic of the region (Sahapedia, undated). These handicrafts have gained national and international recognition and provide a vital supplement to household incomes.

Beyond pastoralism and handicrafts, a third economic activity has grown rapidly in recent years: tourism. The Rann of Kutch, with its surreal white desert landscape, has become a major tourist destination. The Rann Utsav, a three-month cultural festival held from November to February, attracts hundreds of thousands of visitors each year. Dholavira, since receiving its UNESCO World Heritage tag in 2021, has seen a dramatic surge in tourist footfall. This influx of tourists supports a growing local economy of accommodation providers, transport operators, guides, food stalls, and handicraft sellers. However, the tourism season is highly concentrated in the cooler winter months (November to February), with footfall declining sharply between April and September due to extreme temperatures. This seasonal concentration creates a boom-and-bust cycle that leaves the local economy highly vulnerable to external shocks, as was dramatically demonstrated during the COVID-19 pandemic.

Agriculture, while constrained by water scarcity and soil salinity, is also practiced on Khadir Island, particularly in the villages of Amrapar, Janan, and Ratanpar. The main crop is *bajra* (pearl millet), a hardy cereal that is well adapted to drought, high temperatures, and saline soils (IMD, 2022). In recent years, farmers have also successfully cultivated cumin, coriander, mustard, and other cash crops, taking advantage of improved rainfall, better market access, and the construction of water-harvesting bunds under the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS) (Indian Express, 2012).

Despite these pockets of agricultural success, the overall picture is one of chronic water insecurity. A traditional source of income that has largely disappeared is the collection of seeds from the *piloodi* tree (*Salvadora persica*). Forty to fifty years ago, dense forests of piloodi covered much of the area. The seeds yield a valuable oil called *kardi oil*, which was used as a

substitute for coconut oil in cosmetic manufacturing (Institute of Rural Management, undated). The tree is exceptionally well-suited to the region because it thrives in saline soil. However, large camel herds from the Rann invaded the area and destroyed most of the piloodi forest, leaving only a few scattered shrubs. This destruction not only deprived villagers of a sustainable livelihood but also aggravated soil erosion and further increased land and water salinity (Institute of Rural Management, undated). Today, organisations like PAG (Preservation and Proliferation of Art and Culture Group) are encouraging villagers to replant piloodi on their farms, providing a nature-based solution for sustainable income generation in a saline environment.

1.4 The Water Crisis on Khadir Island: A Problem Stated

Khadir Island, the primary focus of this thesis, epitomises the water crisis facing all the inhabited parts of the GRK. The island has an area of approximately 315 km² and is home to ten villages: Dholavira, Janan, Ratanpar, Amrapar, Ganeshpar, Bambhanka, Kharoda, Bapuari, Kalyanpar, and Gadhada. The shallow aquifer, which is the main source of water for domestic and agricultural use, is composed of clayey sand, shale, and sandstone layers. Due to the region's geological history—a marine transgression that began around 18,000 years ago and left behind fine-grained, saline-saturated sediments—the shallow groundwater is naturally brackish to saline (Maurya et al., 2013). This inherent salinity is made worse by ongoing seawater intrusion, driven by excessive groundwater abstraction.

The island's water problems are not merely a matter of resource scarcity; they are also a matter of timing and distribution. Over 85% of the annual rainfall and subsequent groundwater recharge occurs within a span of just two to three months during the monsoon (July to September). In contrast, water demand for domestic use, livestock, and agriculture remains relatively constant throughout the year, creating a severe seasonal deficit. During the peak dry month of June, just before the monsoon arrives, the water deficit can reach as high as 89% of total demand.

1.5 The Need for an Integrated Geo-Hydrological Approach

Conventional attempts to address water scarcity on Khadir Island—digging deeper wells, constructing small check dams, trucking in water—have been piecemeal and reactive. They have failed to account for the complex, interconnected nature of the island's hydrogeological system. A sustainable solution requires a fundamentally different approach: an integrated geo-hydrological framework that simultaneously considers the geological and

lithological framework that controls where water can be stored and how it moves, the climatic and hydrological regime that governs when and how much recharge occurs, the spatial distribution of groundwater potential zones mapped using remote sensing and GIS, the dynamics of seawater intrusion modelled using density-dependent numerical codes, and the socio-economic realities of the island's population, including their settlement patterns, livelihoods, and water demands. This thesis develops and applies precisely such an integrated framework to Khadir Island and extends the findings to propose a replicable water resource development plan for the other isolated islands of the Great Rann of Kachchh.

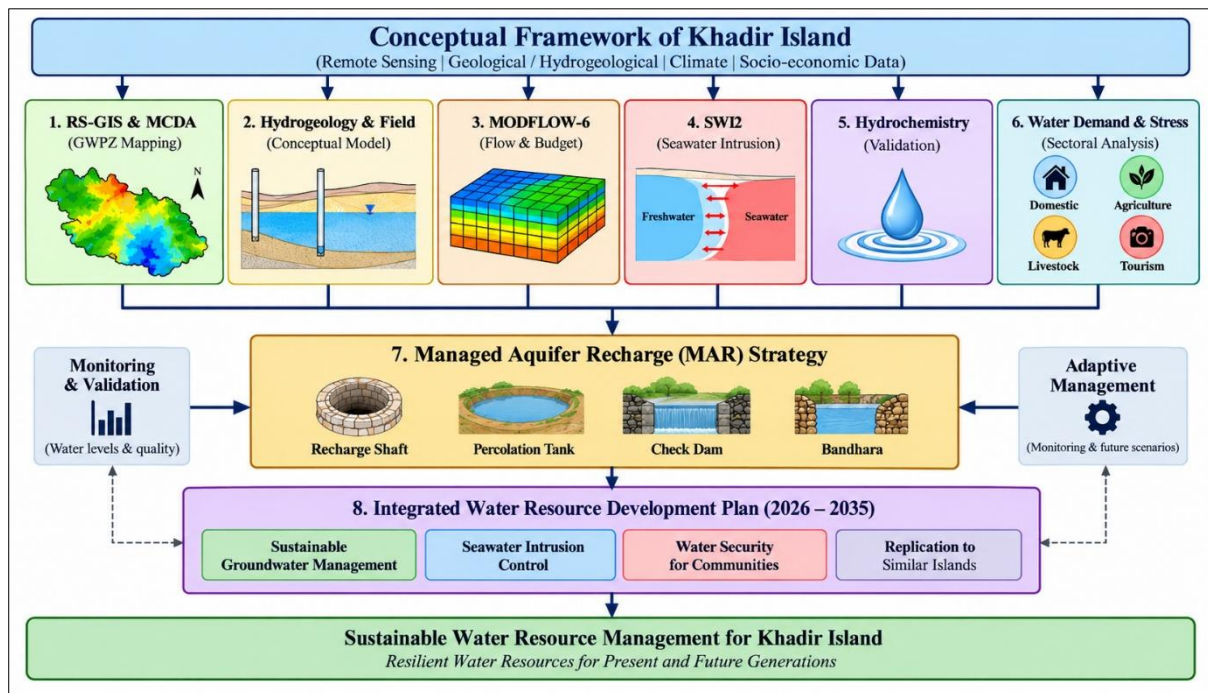


Figure-1.1: Conceptual Frame Work of Khadir Island

1.6 Statement of the Problem

The central problem addressed in this research is the acute and unsustainable freshwater stress faced by the isolated island communities of the Great Rann of Kachchh, with a detailed focus on Khadir Island. This stress is not a single problem but a syndrome of interacting drivers:

1. **Geological predisposition to salinity:** The island's shallow aquifer is composed of marine sediments deposited during a period of high sea level, which inherently contain high levels of soluble salts. This is compounded by ongoing seawater intrusion driven by groundwater abstraction.
2. **Climatic aridity and variability:** Rainfall is low (380–420 mm/year), highly variable from year to year (coefficient of variation ~61%), and concentrated into a short, intense

monsoon. Potential evapotranspiration is more than five times the annual rainfall (IMD, 2022).

3. **A severe temporal mismatch between supply and demand:** The bulk of recharge occurs in a three-month pulse, while demand is relatively constant year-round. This leads to a critical water deficit in the pre-monsoon summer months, culminating in a June deficit of over 100 million litres.
4. **Unsustainable rates of groundwater abstraction:** The Water Exploitation Index (WEI) for the island averages 72.1% over the decade 2011–2020, indicating severe over-exploitation. In dry years, abstraction exceeds renewable recharge by a factor of two or more.
5. **Inefficient water use, particularly in agriculture:** The dominant irrigation method is flood irrigation, with an application efficiency of only around 60%. Approximately 40% of the abstracted water is lost to seepage and evaporation before it ever benefits a crop.
6. **Progressive seawater intrusion:** Numerical modelling shows that under current abstraction rates, the saltwater wedge has advanced from the coastline to reach as far as 6.3 km inland by 2020, with the rate of advance accelerating after 2010.
7. **Limited and fragmented monitoring infrastructure:** Only two long-term monitoring wells exist on the entire island, making it difficult to calibrate models and track trends. This data scarcity is a major challenge that this thesis explicitly addresses through multi-line validation techniques.

1.7 Aim and Objectives of the Research

In line with the registered thesis title—"An Integrated Geo-Hydrological approach towards Water Resource Development plan for the Isolated Islands in the Great Rann of Kachchh, Gujarat, Western India"—this research has the following specific objectives:

1. To characterise the geological, lithological, geomorphological, and hydrogeological framework of Khadir Island and the broader GRK island belt using remote sensing, GIS, and field surveys.

2. To delineate groundwater potential zones (GWPZ) and identify suitable sites for managed aquifer recharge (MAR) using the Multi-Influencing Factor (MIF) method integrated with RS-GIS.
3. To develop a transient groundwater flow model (MODFLOW-6) for Khadir Island, quantify the water budget through zone budget analysis, and assess the sustainability of current abstraction patterns.
4. To simulate seawater intrusion dynamics using a density-dependent sharp-interface approach (MODFLOW-SWI2), validate the model with hydrochemical indicators, and identify critical management thresholds.
5. To quantify the temporal mismatch between water supply and sectoral demand (domestic, agricultural, livestock, tourism) as a basis for designing storage and demand-management interventions.
6. To synthesise the findings into an integrated water resource development plan for the isolated islands of the Great Rann of Kachchh, addressing both hydrogeological and socio-economic dimensions.

1.8 Scope and Limitations of the Study

Scope: The primary study area is Khadir Island (approximately 315 km²). Where relevant published data are available, the analysis extends to other parts of the GRK, including Bela Island and the Banni grasslands. The research covers the period from 2001 to 2023, integrating historical hydro-meteorological data (rainfall, water levels, abstraction) with field campaigns conducted in 2019 and 2021. The methodological framework is designed to be transferable to other arid island and coastal aquifer systems in data-scarce regions globally.

Limitations: The most significant constraint is the sparse long-term monitoring network. Only two wells on Khadir Island have continuous water level records spanning the entire simulation period. This limitation is not concealed but is instead explicitly addressed through a multi-line validation strategy: water balance closure, comprehensive sensitivity analysis, independent hydrogeochemical validation, and comparison of calibrated parameters with published ranges from analogous aquifers. Additional limitations include the use of a sharp-interface approximation for seawater intrusion (which neglects the mixing zone and may slightly underestimate the transition zone width), the absence of explicit climate change scenarios (the

analysis instead uses historical variability as a proxy), and the reliance on secondary socio-economic data from government censuses rather than a primary longitudinal household survey.

1.9 Organisation of the Thesis

This thesis is organised into nine chapters, each addressing a specific component of the research framework and collectively contributing towards the development of an integrated geo-hydrological approach for sustainable water resource management in Khadir Island of the Great Rann of Kachchh.

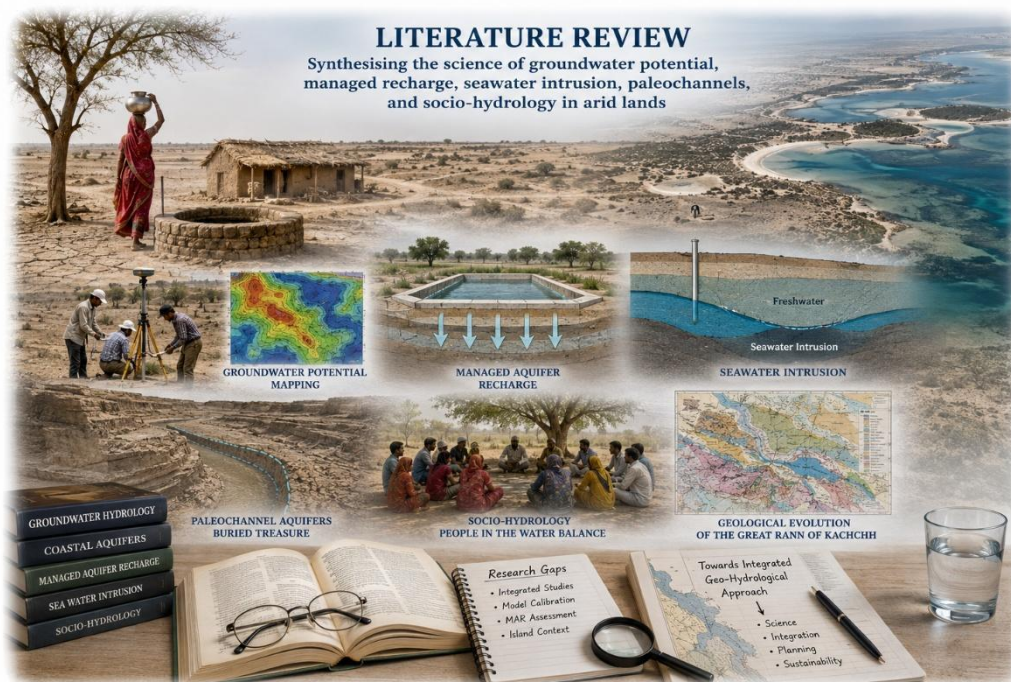
- **Chapter 1** presents the general introduction to the research problem, highlighting the groundwater challenges of Khadir Island and the broader context of water scarcity in arid island environments. The chapter outlines the research objectives, scope, limitations, and significance of the study.
- **Chapter 2** reviews the existing scientific literature related to groundwater potential mapping, managed aquifer recharge, seawater intrusion, palaeochannel aquifers, groundwater modelling, and socio-hydrology in arid and semi-arid regions. The chapter critically evaluates previous studies and identifies the major research gaps addressed in the present work.
- **Chapter 3** describes the study area and field investigations. It presents the regional setting of the Great Rann of Kachchh and detailed characteristics of Khadir Island, including geology, geomorphology, climate, hydrogeology, land use, settlements, and socio-economic conditions. The chapter also discusses the field investigations conducted during 2019 and 2021, including groundwater inventory, lithological observations, hydrochemical sampling, and existing water infrastructure assessment.
- **Chapter 4** explains the research methodology adopted in the study. The chapter describes the integrated RS-GIS-MIF approach for groundwater potential zoning, thematic layer preparation, field data collection protocols, groundwater flow modelling using MODFLOW-6, seawater intrusion assessment using the SWI2 package, water demand estimation procedures, and the multi-line validation framework employed for result verification.
- **Chapter 5** presents the hydrogeological assessment and groundwater management strategy for Khadir Island. The chapter is divided into three major analytical components. The first part presents groundwater potential zoning using the Multi-Influencing Factor (MIF) technique. The second part describes groundwater flow

simulation and zone budget analysis using MODFLOW-6. The third part evaluates seawater intrusion dynamics using the SWI2 package, including hydrogeochemical validation and future projection scenarios up to the year 2025.

- **Chapter 6** develops the Managed Aquifer Recharge (MAR) strategy for Khadir Island. Based on multi-criteria suitability analysis and hydrogeological assessment, the chapter identifies suitable recharge locations and proposes various recharge structures, including recharge shafts, percolation tanks, check dams, and bandharas, for enhancing groundwater sustainability.
- **Chapter 7** assesses water demand, groundwater availability, and water stress conditions of Khadir Island. The chapter evaluates sector-wise water demand trends for domestic, livestock, agricultural, and tourism sectors from 2001 to 2041. It further analyses post-monsoon groundwater availability under different rainfall scenarios and quantifies future water stress conditions using the Water Stress Index (WSI) framework.
- **Chapter 8** synthesises the scientific findings into a practical and phased Integrated Water Resource Development Plan for Khadir Island. The chapter proposes short-term and long-term management interventions integrating recharge enhancement, groundwater conservation, demand management, and community participation for sustainable water resource development. The framework is also designed to be adaptable for other isolated bays of the Great Rann of Kachchh.
- **Chapter 9** summarises the major findings of the research, highlights the original contributions to scientific knowledge, and presents recommendations for groundwater management, policy implementation, and future research directions in arid island environments.

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2.1 Importance of Literature Review in This Study

A strong foundation of knowledge shapes the problem understanding, method selection, and sustainable solutions for Khadir Island. The literature review serves as the backbone of this research by establishing the scientific context within which the study is situated. It provides a systematic examination of existing knowledge across multiple disciplines—hydrogeology, remote sensing, numerical modelling, hydrochemistry, and socio-hydrology—and identifies the specific gaps that justify the present investigation.

The literature contributes to this study in four fundamental ways:

1. First, it provides an understanding of hydrogeological conditions in arid coastal and island environments. Through critical examination of previous research, the review helps identify the critical processes operating in such settings, including seawater intrusion mechanisms, freshwater lens dynamics, and recharge processes under hyper-arid conditions. This process-level understanding is essential for interpreting the field observations and model results presented in subsequent chapters.
2. Second, it supports the selection of appropriate tools and models. The review evaluates various methodological approaches—Remote Sensing and GIS for spatial analysis, MODFLOW for groundwater flow simulation, SWI2 for seawater intrusion modelling, and hydrochemical indicators for model validation—and justifies their application to Khadir Island based on demonstrated success in analogous settings worldwide.
3. Third, it establishes the research gap. Despite extensive research on coastal aquifers globally and on the Kachchh mainland, no integrated, island-specific study has been conducted for Khadir Island or any of the other inhabited bays of the Great Rann of Kachchh. This gap—between what is known and what is needed for sustainable water management—provides the rationale for the present research.
4. Fourth, it forms the foundation for sustainable planning. By synthesising knowledge from multiple disciplines, the review guides the development of a practical, community-centric, 10-year Integrated Water Resource Development Plan that is scientifically rigorous, technically feasible, and socially acceptable.

The conceptual flow from literature to the integrated approach adopted in this thesis is illustrated in Figure 2.1.

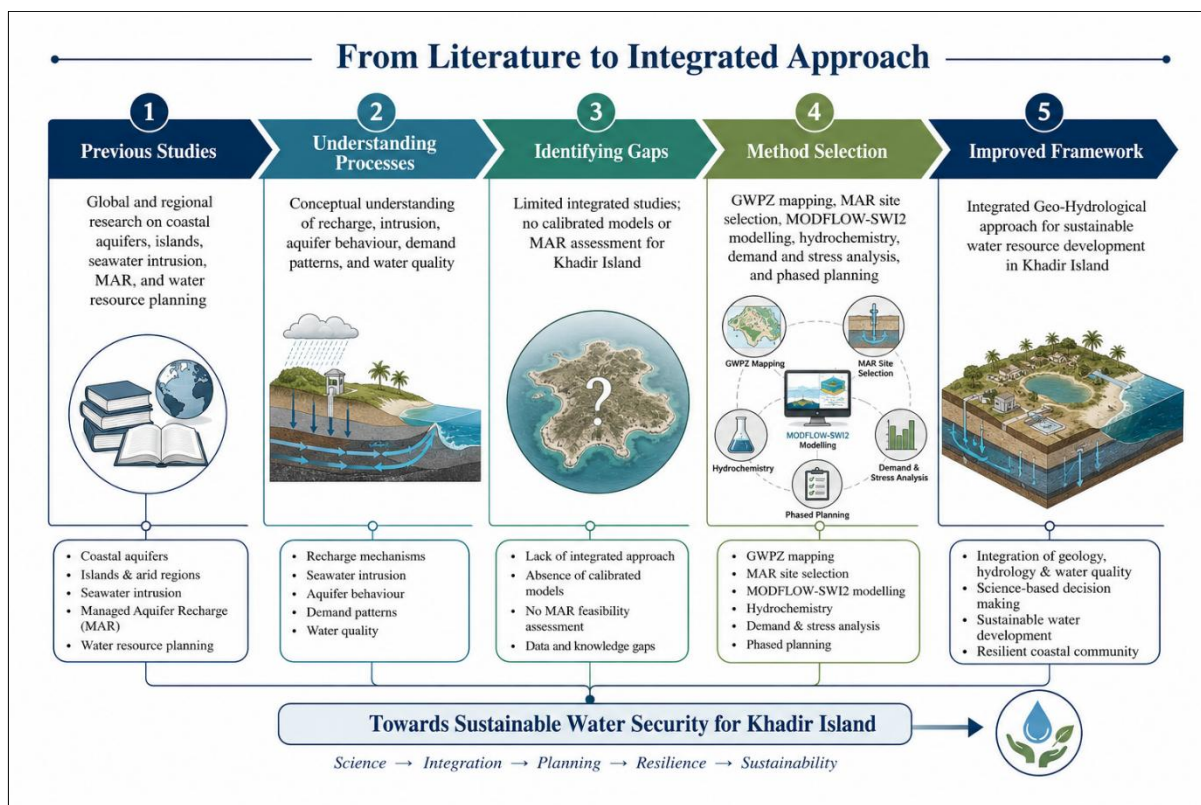


Figure 2.1: From Literature to Integrated Approach frame work

Stage	Description
Previous Studies	Global and regional research on coastal aquifers, islands, seawater intrusion, MAR, and water resource planning
Understanding Processes	Conceptual understanding of recharge, intrusion, aquifer behaviour, demand patterns, and water quality
Identifying Gaps	Limited integrated studies; no calibrated models or MAR assessment for Khadir Island
Method Selection	GWPZ mapping, MAR site selection, MODFLOW-SWI2 modelling, hydrochemistry, demand and stress analysis, and phased planning
Improved Framework	Integrated Geo-Hydrological approach for sustainable water resource development in Khadir Island

The literature reviewed in this chapter demonstrates that robust methodologies are available for groundwater potential mapping, managed aquifer recharge, seawater intrusion assessment, and socio-hydrological analysis. However, these approaches have largely been applied independently and predominantly in mainland or continental settings. An integrated, island-specific assessment for Khadir Island and the inhabited bays of the Great Rann of Kachchh remains limited. To synthesise the existing knowledge and position the present

research within the identified gaps, **Table 2.1** presents a comparative summary of selected previous studies, their methodological approaches, key limitations, identified research gaps, and the contributions of the present study.

Table 2.1: Comparative Summary of Previous Studies and Research Gap

Sr. No.	Previous Studies	Methodology	Key Limitation / Research Gap	Contribution of Present Study
1	Magesh et al. (2012); Das & Pardeshi (2018)	RS-GIS and MIF for GWPZ	Limited application to saline island environments	GWPZ mapping of Khadir Island using eight thematic layers with validation
2	Jha et al. (2010); Rane & Jayaraj (2022)	AHP-based groundwater potential mapping	Subjective weighting; unsuitable for data-scarce settings	MIF-based transparent weighting and multi-parameter validation
3	Bhadra et al. (2021)	RS, HERT and drilling for palaeochannels	Deep aquifers of Khadir Island remain poorly investigated	Identified deep-aquifer potential and proposed deep recharge shaft
4	Werner et al. (2013); Post (2005); White & Falkland (2019)	Seawater-intrusion assessment	Limited application to hyper-arid, data-scarce islands	SWI2 modelling of intrusion dynamics, threshold and future extent
5	Biswas (2005); Maurya et al. (2013); GSI (2015)	Geological and tectonic studies	Regional studies; limited groundwater modelling	3-D transient MODFLOW-6 model with water-budget analysis and validation
6	Sivapalan et al. (2012); Dey & Mandal (2024)	Socio-hydrological assessment	Limited linkage with groundwater modelling	Integrated domestic, agricultural, livestock and tourism water demand

Sr. No.	Previous Studies	Methodology	Key Limitation / Research Gap	Contribution of Present Study
7	Dillon et al. (2020); Bouwer (2002); Maliva (2020)	MAR site selection and design	Limited application to saline island environments	23 MAR structures selected using multi-criteria analysis
8	CGWB (2023); GWRDC (2020)	Groundwater assessment and census	Regional-scale; limited integrated island planning	Five-phase Integrated Water Resource Development Plan (2026–2035)

The importance of this literature review for the present study can be summarised in four key contributions:

1. **Ensures scientific reliability:** The methodology and analysis are based on proven concepts and validated techniques, ensuring that the research outputs are defensible and credible.
2. **Avoids trial-and-error approach:** By building on existing knowledge, the study saves time, resources, and effort that would otherwise be expended on testing unsuitable methods or repeating past mistakes.
3. **Enables integration of multidisciplinary concepts:** The review combines insights from hydrogeology, numerical modelling, remote sensing and GIS, hydrochemistry, and socio-economic analysis into a coherent framework.
4. **Forms the foundation for sustainable planning:** The synthesis of existing knowledge guides the development of a practical, phased, and community-centric 10-year water resource development plan for Khadir Island.

2.2 Overview of the Literature Study

This chapter presents a comprehensive review of the scientific literature relevant to an integrated geo-hydrological approach for water resource development in arid, isolated islands. The review is organised around six thematic pillars: (i) methods for mapping groundwater potential, (ii) managed aquifer recharge as a supply-side intervention, (iii) seawater intrusion processes and modelling, (iv) the role of palaeochannels as alternate freshwater sources, (v) socio-hydrological dimensions that link water availability to livelihoods, and (vi) the

geological evolution of the Great Rann of Kachchh. The chapter concludes by identifying the specific knowledge gaps that this thesis addresses.

The six thematic pillars are not independent but interconnected. Groundwater potential mapping identifies where water is available; managed aquifer recharge provides a means to enhance that availability; seawater intrusion modelling assesses the primary threat to water quality; palaeochannel studies explore alternative sources; socio-hydrology ensures that technical solutions are grounded in community realities; and geological evolution provides the fundamental framework within which all these processes operate. Together, they form a coherent body of knowledge that informs the integrated methodology presented in Chapter 4.

2.2.1 Recent Contributions to Integrated Groundwater Assessment and Coastal Aquifer Management

Recent literature published during **2023–2025** demonstrates a growing shift from individual groundwater assessment techniques towards **integrated, scenario-based and adaptive approaches**. These recent contributions are particularly relevant to the present study because they address the interactions among groundwater flow, recharge, seawater intrusion, climate variability, managed aquifer recharge and water-resource management.

Yang et al. (2023) developed an integrated **SWAT–MODFLOW–SEAWAT** modelling framework to assess groundwater salinization in coastal aquifers under different Shared Socioeconomic Pathway (SSP) scenarios. The study coupled surface-water and groundwater processes and subsequently incorporated SEAWAT for simulation of seawater intrusion. The results demonstrated the usefulness of integrated modelling for evaluating the response of coastal groundwater systems to changing climatic conditions and provided a framework for assessing future salinization.

Stanic et al. (2024) investigated seawater intrusion in a **small island aquifer** considering multiple environmental stressors, including changing recharge, sea-level rise, coastal erosion and storm-surge flooding. A coupled surface–subsurface numerical model was calibrated using field observations and geophysical information. The study demonstrated that reduced recharge and coastal erosion could substantially increase saltwater-wedge migration and that the combined effect of multiple stressors may be more significant than their individual effects. The findings emphasize the importance of considering climate-related and coastal processes together when evaluating the resilience of island groundwater resources.

In the field of managed aquifer recharge, Sheik et al. (2024) reviewed the application of **machine-learning techniques for MAR monitoring and design**. The study examined supervised, semi-supervised, unsupervised and ensemble learning approaches for predicting MAR-related parameters and supporting groundwater management. The authors highlighted the potential of data-driven approaches for improving MAR design, monitoring and groundwater-quality management, while also identifying data availability and technical implementation as important challenges. The article was published online in November 2024 and subsequently assigned to Volume 32 (2025) of *Environmental Science and Pollution Research*.

Table 2.2: Recent Studies Relevant to Integrated Groundwater Modelling and Coastal Aquifer Management (2023–2025)

Sr. No.	Study	Methodology / Focus	Major Contribution	Relevance to Present Study
1	Yang et al. (2023)	SWAT–MODFLOW–SEAWAT; SSP climate scenarios	Integrated surface-water, groundwater-flow and seawater-intrusion modelling under future climate conditions	Supports integrated groundwater-flow and SWI assessment
2	Stanic et al. (2024)	Coupled surface–subsurface modelling; salt transport; climate stressors	Assessed effects of recharge change, sea-level rise, erosion and flooding on a small island aquifer	Supports climate-resilience assessment of island groundwater
3	Sheik et al. (2024)	Machine learning for MAR monitoring and design	Reviewed data-driven approaches for MAR prediction, monitoring and groundwater management	Supports systematic planning and future monitoring of MAR
4	Lyra et al. (2025)	Integrated modelling; MODFLOW, SEAWAT and climate scenarios	Integrated groundwater recharge, water quality and seawater-intrusion assessment	Supports integrated numerical modelling adopted in the thesis

Sr. No.	Study	Methodology / Focus	Major Contribution	Relevance to Present Study
5	Sharan et al. (2025)	3-D numerical model, ML surrogate models, simulation–optimisation and digital twin	Developed an adaptive framework for managing seawater intrusion in an island aquifer	Supports advanced modelling and adaptive island-aquifer management

Lyra et al. (2025) developed an **Integrated Modelling System** for assessing coastal water resources under climate change, irrigation and fertilisation scenarios. The framework combined surface hydrology, groundwater modelling using MODFLOW, solute-transport processes and SEAWAT-based seawater-intrusion assessment. The study considered groundwater recharge, water availability, nitrate concentrations and seawater intrusion within a common modelling framework, demonstrating the increasing importance of integrated groundwater and water-quality assessment for coastal-resource management.

Sharan et al. (2025) further demonstrated the application of advanced modelling approaches through the development of a **digital-twin framework for saltwater-intrusion management in an island coastal aquifer** in Vanuatu. The study combined a three-dimensional numerical model with machine-learning surrogate models and simulation–optimisation techniques to evaluate alternative management scenarios. The authors demonstrated the potential of such frameworks to support adaptive decision-making and management of salinisation risks in vulnerable island aquifers.

These recent contributions strengthen the scientific basis for the integrated approach adopted in the present research. They demonstrate that groundwater-resource assessment is increasingly being undertaken through combinations of **numerical modelling, climate scenarios, geospatial analysis, hydrochemical assessment, MAR planning and adaptive management** rather than through isolated methods. At the same time, the reviewed studies indicate that advanced approaches are often dependent on extensive monitoring data, reliable hydrogeological parameters and continuous model updating. Such requirements can be challenging in data-scarce and environmentally sensitive island environments.

The recent literature also highlights the importance of **linking scientific assessment with practical water-resource planning**. Integrated numerical modelling provides information on groundwater flow and salinity, while spatial approaches identify suitable areas

for groundwater development and MAR. Hydrochemical observations provide field-based evidence for validating groundwater-quality conditions, and water-demand assessment establishes the relationship between available resources and actual or projected requirements. Therefore, an integrated framework is particularly appropriate for isolated islands where groundwater represents a limited and vulnerable freshwater resource.

In the context of **Khadir Island**, these recent developments provide a contemporary scientific basis for combining **RS-GIS-MIF groundwater potential zoning, hydrogeological investigations, MODFLOW-6 groundwater-flow modelling, SWI2 seawater-intrusion simulation, hydrochemical validation, water-demand and water-stress assessment, and MAR planning**. The present study applies these complementary approaches within a single geo-hydrological framework designed specifically for the semi-arid and hyper-saline environment of the Great Rann of Kachchh.

Thus, the literature reviewed in this chapter establishes that the individual scientific methods required for groundwater potential assessment, groundwater-flow modelling, seawater-intrusion assessment, MAR and socio-hydrological planning are well established. However, their **integrated application to an isolated island system such as Khadir Island, where groundwater availability, salinity, recharge variability and sectoral water demand interact simultaneously, remains limited**. This provides the basis for identifying the specific research gaps addressed in the present thesis.

2.3 Groundwater Potential Mapping: From Field Surveys to Remote Sensing

For decades, the identification of areas where groundwater is likely to occur in sufficient quantity and quality relied on expensive and time-consuming field investigations—test drilling, pumping tests, and geophysical surveys. While these methods remain essential for site-specific characterisation, they are not practical for regional-scale assessments, particularly in rugged or inaccessible terrain (Jha et al., 2007; Todd and Mays, 2005).

The advent of satellite remote sensing and geographic information systems (GIS) revolutionised groundwater prospecting. The logic is straightforward: features that can be observed from space—such as landforms, lineaments, soil types, land use, and drainage patterns—are all influenced by, and in turn influence, the occurrence and movement of groundwater beneath the surface (Magesh et al., 2012; Meijerink, 2007). By integrating multiple thematic layers in a GIS environment, researchers can generate a groundwater

potential zone (GWPZ) map that classifies the landscape into categories ranging from "very good" to "poor" based on the combined weight of the controlling factors.

A wide range of multi-criteria decision-making techniques have been used for this purpose. The Analytical Hierarchy Process (AHP), developed by Saaty (1980), is perhaps the most popular. It relies on pairwise comparisons between factors, where experts assign numerical scores based on relative importance. AHP has been successfully applied in diverse settings, from the basaltic aquifers of Maharashtra (Rane and Jayaraj, 2022) to the alluvial plains of West Bengal (Jha et al., 2010). However, AHP has a recognised weakness: it is inherently subjective, and different expert panels can produce different results.

An alternative that reduces subjectivity is the Multi-Influencing Factor (MIF) method. Instead of relying solely on expert judgement for pairwise comparisons, MIF first establishes an inter-relationship matrix among the controlling factors. Each factor is evaluated for the number of "major" and "minor" influences it exerts on other factors. Scores are then calculated as a weighted sum, which is normalised to produce the final factor weights (Magesh et al., 2012; Das and Pardeshi, 2018). The MIF method is simpler and more transparent than AHP, making it particularly attractive for data-scarce regions where expert consensus may be difficult to achieve. Several studies have confirmed that MIF yields results comparable to, and sometimes more realistic than, AHP when applied to the same study area (Rane and Jayaraj, 2022; Sutradhar et al., 2021).

The thematic layers most commonly employed in GWPZ mapping include lithology, geomorphology, lineament density, slope, drainage density, rainfall, land use/land cover, and soil type. Each layer is classified into sub-classes and assigned a rating based on its hydrogeological significance (Arulbalaji et al., 2019; Etikala et al., 2019). Lithology determines primary porosity and permeability; geomorphology indicates landform evolution and recharge potential; lineament density reflects secondary porosity from fractures and faults; slope controls runoff versus infiltration; drainage density is inversely related to permeability; rainfall provides the water input; land use affects surface conditions; and soil type governs infiltration capacity (Yeh et al., 2016; Singh and Kumar, 2017).

In the Indian context, GWPZ mapping using RS-GIS has become routine, with applications ranging from the water-stressed hard rock terrains of Tamil Nadu (Magesh et al., 2012) to the coastal aquifers of Odisha (Kushawaha et al., 2024). Studies in Gujarat have focused primarily on the mainland alluvial and basaltic aquifers (CGWB, 2023), with limited

attention to the unique island aquifer systems of the Great Rann of Kachchh. The application of MIF-based GWPZ mapping to a hyper-saline island environment represents a methodological extension that this thesis provides.

2.4 Managed Aquifer Recharge: A Proven Tool for Arid Regions

Where natural recharge is insufficient to balance groundwater extraction, managed aquifer recharge (MAR) offers a way to intentionally replenish aquifers using surface water, stormwater, or treated wastewater (Dillon et al., 2020). MAR includes a range of techniques, from simple check dams and percolation tanks to more sophisticated recharge wells and aquifer storage and recovery (ASR) systems. In arid and semi-arid regions, MAR has been successfully implemented in countries such as Australia, Spain, the United States, and South Africa (Scanlon et al., 2016; Fernández-Escalante et al., 2018).

The key to a successful MAR project is site selection. Not every location is suitable; the ideal site should have high surface infiltration capacity, good aquifer storage potential, low risk of clogging, and water quality that is compatible with the native groundwater (Bouwer, 2002). GIS-based multi-criteria analysis, often using the same thematic layers as GWPZ mapping, has become the standard method for identifying suitable MAR sites (Aju et al., 2021).

For check dams, the primary siting criteria include: (i) location on an ephemeral stream with a defined channel; (ii) moderate slope (2–10°) to provide sufficient head for infiltration without causing excessive erosion; (iii) moderate to high flow accumulation (indicating sufficient runoff capture potential); and (iv) suitable lithology (sand, gravel, or weathered rock) to allow infiltration (Aju et al., 2021).

For percolation tanks, the siting criteria include: (i) a broad, flat area with low slope (<3°); (ii) fine-to-medium textured soils (sandy loam or loam) with moderate to high infiltration capacity; (iii) distance from built-up areas to avoid contamination; and (iv) location in a moderate to good groundwater potential zone (Bouwer, 2002).

For recharge shafts, the siting criteria include: (i) location in a moderate to good groundwater potential zone; (ii) proximity to a reliable source of water (e.g., canal, stormwater drain); (iii) suitable subsurface lithology (sand or gravel) to accept recharge; and (iv) sufficient depth to avoid clogging (Maliva, 2020).

For bandharas (tidal regulators)—a structure particularly relevant to coastal and island settings—the siting criteria include: (i) location at the mouth of a stream where it meets the

sea; (ii) ability to store monsoon freshwater and prevent tidal ingress; (iii) suitable foundation conditions; and (iv) location upstream of vulnerable extraction wells (Werner et al., 2013).

Despite the proven effectiveness of MAR in diverse settings, its application in hyper-arid island aquifers surrounded by saline water bodies remains limited. The integration of MAR siting with GWPZ mapping and seawater intrusion modelling, as presented in this thesis, addresses this gap.

2.5 Seawater Intrusion in Coastal and Island Aquifers

Seawater intrusion is the landward movement of saline water into freshwater aquifers, driven by density differences and hydraulic gradients. The phenomenon is governed by the Ghyben-Herzberg principle, which states that for every metre of freshwater head above sea level, the freshwater-saltwater interface lies approximately 40 metres below sea level (Bear, 1979). While this relationship provides a useful first approximation, real-world intrusions are more complex, influenced by aquifer heterogeneity, tidal fluctuations, pumping patterns, and climate variability (Werner et al., 2013).

Island aquifers are especially vulnerable because they are entirely surrounded by saline water and have limited storage. The freshwater lens is maintained by a delicate balance between recharge and outflow. When pumping exceeds recharge, the water table drops, the lens thins, and the saltwater wedge advances landward—often irreversibly (Post, 2005). Documented cases of severe intrusion include the Maldives, the Canary Islands, the Hawaiian Islands, and many atolls in the Pacific (White and Falkland, 2019).

Numerical modelling is the primary tool for predicting and managing intrusion. Early models treated the interface as a sharp boundary, simplifying the mathematics but ignoring the mixing zone where fresh and saline water gradually transition. The SWI2 package for MODFLOW (Bakker et al., 2013) implements a sharp-interface approach that is computationally efficient and adequate for regional-scale assessments where the mixing zone is narrow relative to the aquifer thickness. For more detailed studies, variable-density transport codes such as SEAWAT (Langevin et al., 2003) simulate the transition zone explicitly but require much more data and computational effort.

Hydrogeochemical indicators provide independent validation of seawater intrusion models. Key diagnostic ratios include Na^+/Cl^- , $\text{Mg}^{2+}/\text{Ca}^{2+}$, and $\text{Cl}^-/\text{HCO}_3^-$ (Revelle, 1941; Singaraja et al., 2014). Seawater typically has a Na^+/Cl^- ratio of approximately 0.86 by mass,

while freshwater has values greater than 1.0. A ratio below 0.86 in groundwater indicates active seawater mixing (Kushawaha et al., 2024). Elevated Cl^- and Mg^{2+} concentrations, combined with low HCO_3^- , further confirm marine influence. Importantly, the absence of nitrate (NO_3^-) and phosphate (PO_4^{3-}) pollution helps distinguish seawater intrusion from anthropogenic contamination (Krishna Kumar et al., 2014; Reddy et al., 2017).

In the Indian context, seawater intrusion has been documented along the entire west coast, from Gujarat to Kerala, as well as the east coast of Tamil Nadu and Odisha (Kushawaha et al., 2024; Singaraja et al., 2014). However, most studies have focused on heavily populated mainland coastal aquifers. The isolated islands of the Great Rann of Kachchh, despite their extreme vulnerability, had not been the subject of a dedicated seawater intrusion modelling study before this thesis.

2.6 Palaeochannel Aquifers: Buried Treasure in Arid Lands

2.6.1 Global Occurrence and Significance

One of the most exciting developments in arid-zone hydrogeology has been the discovery of palaeochannel aquifers—buried, sand-filled river courses that once flowed across now-dry landscapes. These palaeochannels, often containing high-quality groundwater, have been identified in the Thar Desert of India (Ghose et al., 1979), the Libyan Sahara (Francke, 2016), the United Arab Emirates (Ishola et al., 2024), Australia (Rosen and Jones, 1998), and the southwestern United States (Mace et al., 2000).

Palaeochannel aquifers have several favourable characteristics for water supply: (i) they are typically confined or semi-confined, protected from evaporation and contamination; (ii) the sand-filled channels have high porosity (25–35%) and permeability; (iii) the groundwater is often of better quality than surrounding shallow aquifers because it was recharged during wetter climatic periods (fossil water); and (iv) they can be tapped at depths of 50–200 m, which is within the range of conventional drilling technology.

2.6.2 Exploration Workflow

The standard exploration workflow for palaeochannel aquifers involves three steps (Bhadra et al., 2021; Mace et al., 2000):

1. Step 1: Remote sensing to identify linear geomorphic features that may represent buried river courses. This is typically done using multispectral satellite data (Landsat,

Sentinel) and digital elevation models (SRTM, ALOS PALSAR). Palaeochannels often appear as subtle linear depressions or as bands of different vegetation or soil moisture.

2. Step 2: Geophysical surveys to confirm the presence of sand-filled channels beneath low-resistivity clay caps. The most common method is high-resolution electrical resistivity tomography (HERT), which uses a series of electrodes to measure subsurface resistivity along a transect. Sand (with brackish or fresh water) has higher resistivity than clay (with saline water). A typical resistivity tomogram will show a high-resistivity zone (the palaeochannel) at depth, overlain by a continuous low-resistivity layer (the confining clay).
3. Step 3: Exploratory drilling to verify water quality and yield. Once a target has been identified from geophysics, one or more boreholes are drilled to the predicted depth. Samples are collected for lithological analysis and hydrochemical analysis, and pumping tests are conducted to determine the sustainable yield.

2.6.3 Palaeochannels in the Great Rann of Kachchh

In the Great Rann of Kachchh, this workflow has been successfully applied. Bhadra and colleagues (2021) used multi sensor satellite data (Landsat ETM+, ASTER, and Indian Remote Sensing satellites) to map palaeochannels in the Dharmasala and Gaiinda areas, located near the northern boundary of the GRK. The palaeochannels were identified as linear features with higher soil moisture and different vegetation patterns compared to the surrounding salt flats.

Following remote sensing, HERT surveys were conducted along 710-metre traverses to depths of 250 metres, using the pole-dipole array with 5-metre electrode spacing. The resistivity tomograms showed high-resistivity zones (300–800 ohm-m, interpreted as medium to coarse sand containing brackish water) at depths of 100–150 metres, beneath a thick, continuous low-resistivity layer (5–20 ohm-m, clay with saline water) extending from the surface to about 80 metres depth. This geophysical signature is classic for a confined aquifer system buried under an impermeable, saline-saturated cap.

Exploratory drilling confirmed the presence of confined aquifers below 100 metres, with saturated sand thicknesses of 20–30 metres. Two wells exhibited artesian conditions, with water levels rising above the aquifer top—in one case, water rose to within 10 metres of the surface. The artesian flow is thought to originate from a hydraulic gradient extending from the Tharparkar region in Pakistan, suggesting a regional-scale aquifer system that crosses the international border (Bhadra et al., 2021).

The water quality is reported as "brackish" with total dissolved solids (TDS) in the range of 2,000–5,000 mg/L, which is significantly less saline than the surrounding shallow groundwater (which can exceed 10,000 mg/L). While not suitable for drinking without treatment, this water could be used for livestock and, after desalination, for domestic supply. The presence of artesian conditions also means that pumping costs would be lower than for shallow wells.

2.6.4 Implications for Khadir Island

The discovery of artesian palaeochannel aquifers in the northern GRK has direct implications for Khadir Island. While no deep borehole has yet been drilled on Khadir Island specifically to test for palaeochannels, the geological setting is similar. The island is underlain by the same sedimentary sequence, and lineament mapping shows northeast-southwest trending features that could represent the surface expression of buried channels. Exploring these deep aquifers is a priority for future research, as they could provide an alternative source to reduce pressure on the over-exploited shallow aquifer.

2.7 Socio-Hydrology: Bringing People into the Water Balance

2.7.1 The Emergence of Socio-Hydrology

No water resource development plan can succeed if it ignores the people who depend on that water. Socio-hydrology is an emerging interdisciplinary field that studies the two-way feedbacks between human systems and water systems (Sivapalan et al., 2012). It recognises that water scarcity is not just a physical problem but also a social, economic, and political one.

2.7.2 Pastoralism and Water in the Great Rann

The pastoralist communities of the Great Rann of Kachchh—the Jatts, Maldharis, and others—have developed sophisticated strategies for coping with water scarcity over centuries. These include seasonal migration (moving with their herds to areas where water and fodder are available), collective management of grazing lands, and the use of traditional water harvesting structures (Salot and Mehta, 2004).

However, these strategies are being undermined by a combination of factors (Dey and Mandal, 2024; India Water Portal, 2024):

- Government policies that restrict access to common lands. The declaration of Banni as a Protected Forest in 1955 has been used to limit the movement of pastoralists and has eroded their traditional grazing rights.
- Spread of invasive species that degrade grasslands. The shrub *Prosopis juliflora*, introduced in the 1960s for afforestation, has spread aggressively across Banni, outcompeting native grasses and reducing the carrying capacity of the rangeland.
- Growth of tourism that creates new water demands. The Rann Utsav and the UNESCO World Heritage status of Dholavira have brought thousands of visitors each year, placing additional pressure on the already strained water supply.
- Climate change that increases the frequency of droughts. While the long-term trend in rainfall is not statistically significant, the inter-annual variability is high, and climate models project increased variability and more frequent extreme events for western India (IPCC, 2021).

2.7.3 Livelihoods and Vulnerability

The pastoralist communities—primarily Jatt and Maldhari Muslims—keep herds of Banni buffalo, Kankrej cattle, Kachchhi goats, and Kachchhi camels. Milk and milk products are sold to cooperatives and private traders, generating the bulk of household income (India Water Portal, 2024). A detailed cross-sectional study of the Banni economy found that the sale of milk and milk products generated the highest average annual net income of approximately ₹414,070 per household, contributing as much as 82% to the region's total economy.

The Hindu Meghwal and Vadha Koli communities, while also keeping some livestock, are renowned for their embroidery, leatherwork, wood-carving, and the construction of bhungas (traditional circular mud houses). These handicrafts have gained national and international recognition and provide a vital supplement to household incomes.

Tourism is a rapidly growing sector, centred on the UNESCO World Heritage site of Dholavira. The site now receives approximately 150,000 visitors annually. However, the tourism season is highly concentrated in the cooler winter months (November to February), creating a boom-and-bust cycle that leaves the local economy highly vulnerable to external shocks, as demonstrated during the COVID-19 pandemic.

A socio-economic vulnerability assessment using RIDIT scoring examined two tourism-dependent villages in the Rann of Kutch region, identifying essential vulnerability parameters including water availability, healthcare access, fodder availability, roads, and mobile phone coverage (Dey and Mandal, 2024). This research highlights the need for diversified livelihood options and improved infrastructure, including reliable water supply, to reduce community vulnerability.

2.7.4 Agriculture and Traditional Livelihoods

Agriculture is practiced on about one-third of Khadir Island, primarily in the central and eastern villages. The main crop is bajra (pearl millet), followed by cumin, coriander, mustard, and vegetables (IMD, 2022). However, agriculture is risky due to the high variability of rainfall and the increasing salinity of irrigation water.

A traditional livelihood that is being revived is the cultivation of piloodi (*Salvadora persica*), a salt-tolerant tree whose seeds yield a valuable oil used in cosmetics. The piloodi forest was largely destroyed by camel grazing decades ago, but organisations such as PAG (Preservation and Proliferation of Art and Culture Group) are encouraging farmers to replant the tree on their farms. This represents a nature-based solution for sustainable income generation in a saline environment (Institute of Rural Management, undated).

2.7.5 Infrastructure Gaps

Rural infrastructure in the bet areas remains underdeveloped. Historical accounts note the absence of primary health centres, with private doctors visiting once fortnightly (Institute of Rural Management, undated). Contemporary assessments confirm persistent gaps in water availability, healthcare access, fodder availability, roads, schools, and cell phone coverage (Dey and Mandal, 2024; India Water Portal, 2024). Specific infrastructure gaps relevant to water security include: no piped water supply to most households, no desalination plant despite brackish groundwater, inadequate storage for monsoon runoff, limited electricity for pumping, and no groundwater monitoring network beyond the two CGWB/GWRDC wells.

2.8 Geological Evolution of the Great Rann of Kachchh

2.8.1 Tectonic Setting

The GRK is not a static landscape but a dynamic geological feature shaped by tectonic activity and sedimentation over millions of years. It is bounded by the Nagar Parker Fault

(NPF) to the north and the Kachchh Mainland Fault (KMF) to the south. The region has experienced significant tectonic instability throughout the Quaternary period (Biswas, 2005; Maurya et al., 2013).

Originally, the GRK was an extension of the Arabian Sea. It was gradually closed off by silting, and its current form reflects uplift during faulting events. The most significant historical event was the 1819 Allah Bund earthquake, which created a northeast-southwest trending scarp approximately 90 km long and up to 6 m high, dramatically altering the drainage and inundation patterns of the region (Rajendran and Rajendran, 2001).

2.8.2 Marine Transgression and Late Quaternary History

Radiocarbon dating of sediment cores has provided critical chronological control. An age of $17,700 \pm 86$ cal years BP was obtained from the Dhordo core at 60.13 m depth, and $9,515 \pm 61$ cal years BP from the basal marine sequence in the Berada core at 38.88 m depth (Maurya et al., 2013). These dates indicate that the central GRK basin was submerged by a shallow sea by approximately 18,000 years ago, whereas marginal areas including the Banni plain were completely submerged by approximately 10,000 years ago.

The presence of foraminifera (marine microfossils) throughout the core sections confirms marine sedimentation throughout the late Quaternary. This finding has profound implications for groundwater occurrence, as the marine origin of sediments contributes to the inherent salinity of the shallow aquifer system.

The stratigraphic succession includes the Jhurio Formation (Early Jurassic limestone and shale), Jumara Formation (Middle Jurassic shale and limestone), Jhuran Formation (Late Jurassic sandstone and shale), and Bhuj Formation (Early Cretaceous sandstone). These Mesozoic formations are overlain by Deccan Trap basalts and Paleogene-Neogene sediments, culminating in the Quaternary sediments of the Rann (Biswas, 2005; GSI, 2015). The geological framework controls both the geometry and the hydraulic properties of the aquifer system on Khadir Island.

2.9 Identification of Research Gaps

The literature reviewed in Sections 2.3 to 2.8 demonstrates substantial progress in groundwater-potential mapping, groundwater-flow modelling, seawater-intrusion assessment, hydrogeochemical investigations, Managed Aquifer Recharge (MAR), palaeochannel studies, and water-resource management. However, these approaches have predominantly been

developed and applied as individual components, with comparatively limited integration within the specific hydrogeological setting of isolated and saline island systems.

In particular, the reviewed literature indicates that the **Great Rann of Kachchh (GRK)** presents a distinctive combination of arid climatic conditions, highly variable recharge, saline surroundings, thin freshwater lenses, groundwater dependence, and socio-economic water requirements. These characteristics create a need for an integrated assessment that combines groundwater potential, hydrogeology, groundwater flow, seawater intrusion, hydrochemistry, palaeochannel potential, water availability, water demand, recharge interventions, and management planning.

Based on the comprehensive literature review and comparative assessment of previous studies, six specific research gaps have been identified, as summarised in Table 2.4.

1. No systematic GWPZ mapping for Khadir Island: While RS-GIS-MIF methods have been widely applied in mainland India, their application to the unique hyper-saline island environment of the Great Rann has been absent.

2. Lack of integrated groundwater flow and seawater intrusion models for the GRK islands: Numerical modelling studies have been conducted for the Kachchh mainland, but not for the isolated bays, which have very different boundary conditions (surrounded by saline water, thin freshwater lens).

3. No quantification of the temporal mismatch between supply and demand: The seasonal concentration of recharge and the year-round pattern of demand have been described qualitatively, but not quantified in a way that can guide intervention design.

4. Insufficient integration of hydrogeochemical and modelling approaches for validation: In data-scarce settings, model validation is challenging. The use of diagnostic ionic ratios (Na^+/Cl^- , $\text{Mg}^{2+}/\text{Ca}^{2+}$, $\text{Cl}^-/\text{HCO}_3^-$) as independent lines of evidence has been underutilised.

5. Limited integration of palaeochannel potential into groundwater-resource planning: While palaeochannels are recognised as potentially important groundwater-bearing features, their integration with GWPZ mapping, groundwater-flow assessment, and recharge planning has been limited for the GRK islands.

6. Lack of a unified water resource development plan for the GRK islands: While individual components (e.g., palaeochannel exploration, check dam construction) have been

attempted, no study has proposed an integrated plan that combines GWPZ mapping, MAR, seawater intrusion control, palaeochannel development, and socio-economic considerations in a single framework. This thesis provides such a plan.

Table 2.3: Consolidated Summary of Identified Research Gaps and Responses in the Present Thesis

Sr. No.	Identified Research Gap	Response in Present Thesis
1	No systematic GWPZ mapping for Khadir Island	Eight-layer RS-GIS-MIF GWPZ mapping with field and hydrochemical validation
2	Lack of integrated groundwater flow and seawater intrusion models for GRK islands	MODFLOW-6 flow model coupled with SWI2 seawater intrusion model
3	No quantification of the temporal mismatch between supply and demand	Water availability (2011–2025), sectoral demand, and Water Stress Index (2026–2030)
4	Insufficient integration of hydrogeochemical and modelling approaches for validation	Diagnostic ionic ratios (Na^+/Cl^- , $\text{Mg}^{2+}/\text{Ca}^{2+}$, $\text{Cl}^-/\text{HCO}_3^-$) used as independent validation of SWI2 results
5	Limited integration of palaeochannel potential into groundwater-resource planning	Palaeochannel identification incorporated into hydrogeological interpretation and deep recharge shaft proposal (RS-23)
6	Lack of a unified water resource development plan for the GRK islands	Integrated Water Resource Development Plan (2026–2035) with 23 MAR structures and phased implementation

The identified gaps collectively demonstrate the need for an approach that moves beyond isolated assessment of individual groundwater components. The present thesis therefore adopts an integrated geo-hydrological framework in which groundwater potential, hydrogeology, groundwater flow, seawater intrusion, hydrochemistry, palaeochannel potential, water demand, water stress, and managed aquifer recharge are evaluated as interconnected

components of the same water-resource system. This integrated framework forms the basis for developing a sustainable and phased water-resource development strategy for Khadir Island.

2.10 Summary of the Chapter

This chapter has presented a comprehensive review of the scientific literature related to groundwater occurrence, assessment, and management in arid and semi-arid environments, with particular emphasis on island hydrogeological systems. Key thematic areas examined include groundwater potential zone (GWPZ) mapping using remote sensing and GIS techniques, managed aquifer recharge (MAR) strategies, mechanisms and impacts of seawater intrusion, the hydrogeological significance of palaeochannel aquifers, emerging concepts in socio-hydrology, and the geological evolution of the Great Rann of Kachchh (GRK).

The review highlights that remote sensing and GIS-based approaches, including **Multi-Influencing Factor (MIF)**, **Analytical Hierarchy Process (AHP)**, and **Frequency Ratio (FR)** methods, have been widely applied for delineating groundwater potential zones with reasonable accuracy. However, most studies have been undertaken in continental or mainland settings and often rely on a restricted set of parameters. The complexities of coastal and island aquifers, where freshwater may occur as relatively fragile lenses overlying or adjoining saline water, require a more integrated assessment of hydrogeological, geological and spatial controls.

Similarly, MAR techniques such as **recharge shafts, percolation tanks, check dams and other recharge structures** have demonstrated their potential for enhancing groundwater recharge under different hydrogeological conditions. Nevertheless, their application in arid island environments remains relatively limited, particularly where groundwater systems are influenced by saline conditions, coastal processes and highly variable recharge. The literature further indicates that seawater intrusion is a major challenge in coastal aquifers and is controlled by factors such as hydraulic gradients, groundwater abstraction, recharge conditions, aquifer characteristics and coastal processes. However, the direct integration of seawater-intrusion assessment with groundwater recharge and water-resource planning remains insufficiently addressed in many studies.

Studies on palaeochannel aquifers indicate their potential significance as preferential groundwater-flow and storage zones because of their relatively favourable permeability and depositional characteristics. However, systematic integration of palaeochannel identification with groundwater potential assessment, hydrogeological modelling and recharge-site selection remains limited. In addition, the emerging field of socio-hydrology emphasizes the importance

of understanding human–water interactions, land-use practices, resource dependence and community participation in sustainable groundwater management. Nevertheless, the integration of these socio-hydrological considerations with numerical groundwater assessment and practical water-resource development planning is still relatively uncommon.

From a regional perspective, existing studies of the **Great Rann of Kachchh** have provided valuable information concerning its geological evolution, tectonic setting, sedimentary processes and hydrogeological characteristics. However, an integrated assessment that simultaneously considers groundwater potential, groundwater flow, seawater intrusion, hydrochemical characteristics, water demand, recharge interventions and socio-economic requirements of the isolated **bet islands**, particularly Khadir Island, remains limited.

Recent studies published during **2023–2025** further demonstrate the increasing importance of integrated approaches in groundwater and coastal-aquifer research. Recent applications of coupled **SWAT–MODFLOW–SEAWAT** modelling have linked groundwater salinization with climate scenarios, while studies of small island aquifers have incorporated changing recharge, sea-level rise, coastal erosion and coastal flooding into seawater-intrusion assessments. Recent research has also explored machine-learning applications for MAR monitoring and design, integrated groundwater and coastal-water modelling under climate and irrigation scenarios, and digital-twin and simulation–optimisation approaches for managing saltwater intrusion in island aquifers. These developments demonstrate a clear shift towards **integrated, scenario-based and adaptive groundwater management**. However, such approaches can require extensive monitoring data, reliable hydrogeological parameters and continuous model updating, which may be difficult to achieve in data-constrained island environments.

The recent literature therefore strengthens the scientific basis for combining **spatial analysis, hydrogeological investigation, numerical modelling, hydrochemical assessment, recharge planning and water-demand analysis** within a common framework. At the same time, the reviewed studies indicate that these components are frequently developed or applied separately and in hydrogeological settings that differ substantially from the semi-arid and hyper-saline environment of the Great Rann of Kachchh.

Overall, the literature review reveals that robust methodologies and datasets exist for individual components such as **GWPZ mapping, MAR assessment, groundwater-flow modelling, seawater-intrusion analysis, hydrochemical evaluation and water-demand**

assessment. Recent advances have further demonstrated the value of integrated numerical, geospatial, climate-scenario and data-driven approaches. Nevertheless, there remains a research gap in their systematic integration for an isolated and environmentally sensitive island aquifer system such as Khadir Island.

The present study addresses these gaps by integrating **remote sensing and GIS-based Multi-Influencing Factor (MIF) analysis, field hydrogeological investigations, palaeochannel identification, hydrochemical assessment, MODFLOW-6 groundwater-flow modelling, SWI2 seawater-intrusion modelling, water-demand and water-stress assessment, and Managed Aquifer Recharge (MAR) planning** into a single geo-hydrological framework. The framework is further extended to develop a phased water-resource development strategy for Khadir Island, thereby establishing a direct linkage between **groundwater assessment, groundwater protection, demand management, recharge enhancement and long-term water-resource planning.**

The subsequent chapters build upon this literature foundation to develop, apply and validate the integrated geo-hydrological methodology for sustainable water-resource development of **Khadir Island in the Great Rann of Kachchh.**

"An integrated framework of RS-GIS, field investigations, and multi-disciplinary analysis for sustainable groundwater management"

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3.1 INTRODUCTION

This chapter presents the comprehensive methodological framework developed and applied in this research to assess groundwater potential, quantify aquifer dynamics, evaluate seawater intrusion, and formulate a sustainable water resource development plan for Khadir Island. The methodology integrates remote sensing (RS) and geographic information systems (GIS), multi-criteria decision analysis (MCDA), numerical groundwater flow and transport modelling, hydrogeochemical analysis, field investigations, and socio-economic assessment into a coherent, multi-disciplinary research design.

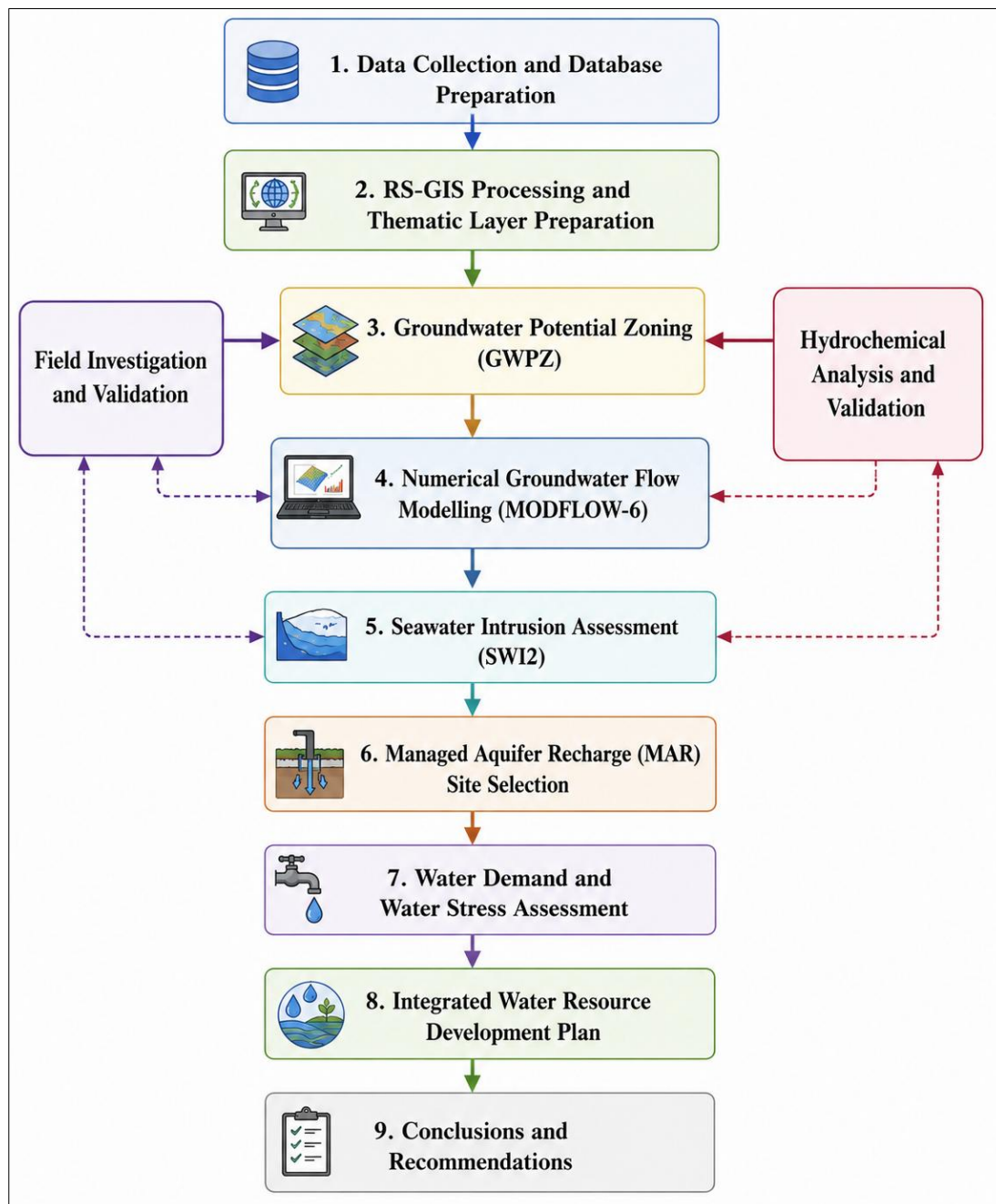


Figure 3.1: Methodological Flow Chart of the Work

The methodological approach is guided by the recognition that sustainable groundwater management in data-scarce, arid island environments requires the integration of multiple lines of evidence. No single technique—whether satellite-based mapping, numerical simulation, or field survey—can alone provide a complete understanding of the complex hydrogeological system operating on Khadir Island. Instead, each method contributes a critical component, and their integration provides a robust scientific basis for planning and decision-making.

The methodology follows a structured nine-step workflow, as illustrated in Figure 4.1. Each step is designed to build upon the outputs of the preceding step, creating a logical progression from data acquisition through analysis to the final synthesis of an Integrated Water Resource Development Plan.

Table 3.1: Methodology Flow Chart

Step	Activity	Output
1	Data Collection and Database Preparation	Comprehensive geospatial and hydro-meteorological database
2	RS-GIS Processing and Thematic Layer Preparation	Eight thematic layers
3	Groundwater Potential Zoning (GWPZ)	GWPZ map (Good, Moderate, Poor zones)
4	Numerical Groundwater Flow Modelling (MODFLOW-6)	Calibrated flow model, zone budget
5	Seawater Intrusion Assessment (SWI2)	Intrusion progression (2001–2020), critical thresholds
6	Managed Aquifer Recharge (MAR) Site Selection	23 proposed MAR structures
7	Water Demand and Water Stress Assessment	Demand projections (2001–2041), WSI analysis (2026–2030)
8	Integrated Water Resource Development Plan	Phased 10-year implementation plan
9	Conclusions and Recommendations	Key findings, contributions, policy recommendations

3.2 STEP 1: DATA COLLECTION AND DATABASE PREPARATION

The first step of the methodology involved the systematic collection of all primary and secondary data required for the study. A comprehensive geospatial database was constructed comprising satellite imagery, digital elevation models, geological and hydrogeological maps, hydro-meteorological data, groundwater monitoring records, and socio-economic information.

3.2.1 Satellite Data

Multi-temporal and multi-spectral satellite data were acquired for three representative seasons (pre-monsoon, post-monsoon, and summer) to capture seasonal variability in surface conditions. Table 4.1 summarises the satellite data sources used in this study.

Table 3.2: Satellite Data Used in This Study

Satellite / Sensor	Resolution	Purpose	Source
Landsat-8 OLI/TIRS	30 m (multispectral), 15 m (panchromatic)	Lithology, geomorphology, lineament mapping	USGS Earth Explorer
Sentinel-2 MSI	10 m (visible/NIR), 20 m (SWIR)	LULC classification, detailed geomorphology	ESA Copernicus Open Access Hub
SRTM DEM	30 m	Elevation, slope, drainage, flow accumulation	USGS Earth Explorer
Cartosat-1	2.5 m (panchromatic)	Validation of LULC and lineaments	ISRO Bhuvan

3.2.2 Geological and Hydrogeological Data

Geological maps of the Kachchh district were obtained from the Geological Survey of India (GSI) Bhukosh portal at 1:250,000 scale. These maps provided information on lithological units, structural features (faults, lineaments), and stratigraphic succession. Hydrogeological data, including aquifer parameters, water level records, and groundwater quality data, were obtained from the Central Ground Water Board (CGWB) and the Gujarat Water Resources Development Corporation (GWRDC).

3.2.3 Hydro-Meteorological Data

Rainfall data for the period 2001–2020 were obtained from the India Meteorological Department (IMD) gridded dataset at $0.25^{\circ} \times 0.25^{\circ}$ spatial resolution. Temperature and

evapotranspiration data were obtained from IMD climatological records and the FAO CLIMWAT database.

3.2.4 Socio-Economic Data

Population data were obtained from the Census of India (2001 and 2011), projected to 2021 using decadal growth rates. Livestock statistics were obtained from the District Animal Husbandry Department, Kachchh. Agricultural data, including crop types, cropping patterns, and irrigation practices, were collected through farmer interviews during field campaigns and from the Agriculture Department, Kachchh. Tourism data were collected from the Gujarat Tourism Department and published literature.

3.3 STEP 2: RS-GIS PROCESSING AND THEMATIC LAYER PREPARATION

The second step involved the processing of satellite imagery and the preparation of thematic layers that serve as inputs for groundwater potential mapping, managed aquifer recharge site selection, and hydrogeological characterisation.

3.3.1 Image Pre-processing

All satellite images were pre-processed to correct for atmospheric and geometric distortions. Atmospheric correction was performed using the Dark Object Subtraction (DOS) method (Chavez, 1996). Geometric correction was performed using ground control points (GCPs) collected during the 2019 and 2021 field campaigns, with a root mean square error (RMSE) of less than 0.5 pixels. All datasets were projected to the Universal Transverse Mercator (UTM) coordinate system, Zone 42 North, using the WGS 84 datum.

The SRTM DEM was pre-processed by filling sinks using the "Fill" tool in ArcGIS 10.8 to ensure continuous flow paths for drainage extraction. The filled DEM was then used to derive slope, aspect, drainage network, and flow accumulation rasters using the Spatial Analyst and Hydrology toolset.

3.3.2 Thematic Layer Preparation

A total of eight thematic layers were prepared in ArcGIS 10.8 for groundwater potential mapping and hydrogeological assessment. Each thematic layer was converted to raster format with a uniform cell size of 30 m × 30 m, classified into sub-classes based on hydrogeological significance, and assigned ratings on a 1–10 scale. The eight thematic layers are:

1. **Lithology:** Prepared from GSI geological maps (1:250,000 scale), refined through satellite image interpretation and validated during field surveys. Five lithological units were mapped: Clayey Sand, Khari Shale, Kanakavati Pink Sandstone, Jhurio Shell-Limestone, and Sandy Shale.
2. **Geomorphology:** Prepared from Landsat-8 and Sentinel-2 image interpretation, supported by SRTM DEM analysis and field validation. Five geomorphic units were identified: Alluvial Plain, Denudational Hill, Pediplain, River/Water Bodies, and Structural Hill.
3. **Lineament Density:** Prepared from Landsat-8 and Sentinel-2 imagery using directional filtering, principal component analysis, and visual interpretation. Lineament density was calculated using the Line Density tool in ArcGIS.
4. **Rainfall:** Prepared from IMD gridded rainfall data ($0.25^\circ \times 0.25^\circ$) using inverse distance weighted (IDW) interpolation. The long-term mean annual rainfall (2001–2020) was used.
5. **Slope:** Derived from the SRTM DEM using the Slope tool in ArcGIS Spatial Analyst. Slope was classified into five categories: Nearly Level ($0-2^\circ$), Gentle ($2-5^\circ$), Moderate ($5-10^\circ$), Moderately Steep ($10-15^\circ$), and Steep ($15-30^\circ$).
6. **Drainage Density:** Calculated from the drainage network extracted from the SRTM DEM using the Line Density tool. Drainage density represents the total length of stream channels per unit area (km/km^2).
7. **Land Use/Land Cover (LULC):** Prepared using supervised classification (Maximum Likelihood algorithm) of Sentinel-2 imagery for the years 2001, 2010, and 2020. Six LULC classes were identified: Water Bodies, Trees/Forest, Agriculture, Built-up Area, Bare Land, and Rangeland.
8. **Soil Type:** Prepared from digitised FAO soil maps and refined through field observations. Five soil types were identified: Sandy Clay Loam, Clay Loam, Clayey Soils, Coastal/Saline Clay, and Sandy Soils/Sand Dunes.

3.3.3 Software Environment

All RS-GIS analyses were carried out using ArcGIS 10.8 (ESRI, 2020) for spatial data management, thematic layer generation, spatial analysis, weighted overlay modelling, and map

preparation. Google Earth Pro was utilized for satellite image visualization, location verification, coordinate extraction, and support for field validation activities. Numerical groundwater modelling was performed using ModelMuse 4.4.3 (Winston, 2009) as the graphical user interface for MODFLOW-6 and the SWI2 package. Statistical analyses, data processing, and graphical representations were prepared using Microsoft Excel.

3.4 STEP 3: GROUNDWATER POTENTIAL ZONING (GWPZ)

The third step involved the delineation of Groundwater Potential Zones (GWPZ) using the Multi-Influencing Factor (MIF) method integrated with RS-GIS.

3.4.1 Multi-Influencing Factor (MIF) Method

The MIF method was selected for weight assignment because it reduces the subjectivity inherent in expert-based methods such as the Analytical Hierarchy Process (AHP) by first establishing an inter-relationship matrix among the controlling factors (Magesh et al., 2012; Das and Pardeshi, 2018). Each factor is evaluated for the number of "major" influences (score = 1.0) and "minor" influences (score = 0.5) it exerts on other factors. Scores are then normalised to produce the final factor weights.

3.4.2 Weighted Overlay Analysis

The eight thematic layers were integrated using the Weighted Overlay tool in ArcGIS 10.8. The GWPZ map was classified into three categories—Good, Moderate, and Poor—using the Natural Breaks (Jenks) classification method (Jenks, 1967).

3.4.3 Validation

The GWPZ map was validated using long-term hydrochemical data (TDS, Cl^- , Na^+/Cl^- ratios) from two government monitoring wells: KC-13 at Dholavira (Good zone) and HPII_KCH_006 at Kalyanpar (Poor zone).

The detailed methodology for the MIF analysis, including the inter-relationship matrix, weight calculation, and feature ratings, is presented in Chapter 5 (Part A: Groundwater Potential Zoning).

3.5 STEP 4: NUMERICAL GROUNDWATER FLOW MODELLING (MODFLOW-6)

The fourth step involved the development of a transient three-dimensional groundwater flow model for Khadir Island using MODFLOW-6. The model simulated groundwater flow dynamics over the period 2001–2020 by incorporating spatially distributed recharge, pumping stresses, aquifer properties, and boundary conditions. Hydrogeological information derived from field investigations and lithological interpretations was integrated into the

model framework to represent the multilayer aquifer system. Calibration and validation were performed using observed groundwater levels to evaluate model performance. The calibrated groundwater flow model subsequently served as the basis for zone budget analysis and for coupling with the SWI2 package to assess seawater intrusion processes and future groundwater sustainability scenarios.

3.5.1 Model Setup

The model was developed within the ModelMuse 4.4.3 environment (Winston, 2009). MODFLOW-6 solves the three-dimensional groundwater flow equation using a generalised control-volume finite-difference approach (Langevin et al., 2017). The governing equation is:

$$\partial/\partial x (K_{xx} \partial h/\partial x) + \partial/\partial y (K_{yy} \partial h/\partial y) + \partial/\partial z (K_{zz} \partial h/\partial z) + q_s = S_s (\partial h/\partial t)$$

where K_{xx} , K_{yy} , K_{zz} are hydraulic conductivity values (L/T), h is hydraulic head (L), q_s is volumetric flux per unit volume (1/T), S_s is specific storage (1/L), and t is time (T).

3.5.2 Model Domain and Discretisation

The model domain covers approximately 352 km², discretised into 107 rows × 58 columns with 300 m × 300 m cells (6,264 total cells, 4,954 active cells). Four hydrostratigraphic layers represent: Layer 1 (Shallow Aquifer: Sandhan Formation, 0–45 m), Layer 2 (Principal Aquifer: Jhuran Formation sandstone, 45–150 m), Layer 3 (Semi-Confined: Jhuran Formation silty sandstone, 150–220 m), and Layer 4 (Basal Aquitard: Jhumra Formation limestone and shale, 220–300 m).

3.5.3 Simulation Period and Boundary Conditions

The transient simulation covers 2001–2020 (20 years) with 80 quarterly stress periods. Boundary conditions include: Specified Head (CHD) on the eastern boundary, Recharge (RCH) from rainfall on Layer 1, Well (WEL) abstraction, River (RIV) for ephemeral streams, Evapotranspiration (EVT) from shallow groundwater, and General Head Boundary (GHB) along the western and southern coastal margins.

3.5.4 Calibration and Zone Budget

Model calibration was performed by trial-and-error adjustment of hydraulic conductivity, recharge, and storage parameters to match observed hydraulic heads from two long-term monitoring wells. A zone budget analysis quantified volumetric exchanges between layers and across boundaries.

The detailed methodology for model setup, parameterisation, calibration, and zone budget analysis is presented in Chapter 5 (Part B: Groundwater Flow Modelling and Zone Budget).

3.6 STEP 5: SEAWATER INTRUSION ASSESSMENT (SWI2)

The fifth step involved the assessment of seawater intrusion dynamics using a density-dependent numerical model.

3.6.1 Sharp-Interface Approach

The seawater intrusion model was developed using the SWI2 (Seawater Intrusion) package for MODFLOW (Bakker et al., 2013) within ModelMuse 4.4.3. The SWI2 package implements a sharp-interface approach governed by the Ghyben-Herzberg principle (Bear, 1979):

$$z = [\rho_f / (\rho_s - \rho_f)] \times h$$

where z is interface depth below mean sea level (m), h is freshwater head above mean sea level (m), ρ_f is freshwater density (1,000 kg/m³), and ρ_s is seawater density (1,025 kg/m³). The density ratio of approximately 40 implies that a 1 m decline in freshwater head allows the interface to rise by approximately 40 m.

3.6.2 Model Setup and Simulation

The SWI2 model uses the same grid and boundary conditions as the MODFLOW-6 flow model. The transient simulation was run for 20 years (2001–2020) under sustained pumping stress of 5 L/s. The initial interface position was set at equilibrium assuming pre-development heads.

3.6.3 Sensitivity Analysis

A one-parameter-at-a-time sensitivity analysis was conducted to quantify the influence of recharge, pumping rate, hydraulic conductivity, and specific yield on the predicted intrusion distance (Dettinger and Wilson, 1981).

3.6.4 Hydrogeochemical Validation

Model results were validated using independent hydrochemical data, including TDS, Cl⁻ concentrations, and Na⁺/Cl⁻ ratios from government monitoring wells. Diagnostic ionic ratios (Na⁺/Cl⁻, Mg²⁺/Ca²⁺, Cl⁻/HCO₃⁻) were used to distinguish seawater intrusion from other salinity sources (Revelle, 1941; Singaraja et al., 2014). This integrated approach enabled both numerical and hydrochemical verification of the simulated seawater intrusion processes within the aquifer system. The detailed methodology for model setup, sensitivity analysis, and hydrogeochemical validation is presented in Chapter 5 (Part C: Seawater Intrusion Assessment).

3.7 STEP 6: MANAGED AQUIFER RECHARGE (MAR) SITE SELECTION

The sixth step involved the identification of suitable sites for managed aquifer recharge (MAR) structures based on multi-criteria decision analysis.

3.7.1 Multi-Criteria Site Suitability

MAR site suitability was evaluated by integrating the GWPZ map with additional criteria derived from the thematic layers, including drainage characteristics, slope, lineament density, and soil permeability (Aju et al., 2021; Bouwer, 2002; Dillon et al., 2020).

3.7.2 Structure Types and Siting Criteria

Four types of MAR structures were considered with specific siting criteria:

- **Recharge Shafts:** Good/Moderate GWPZ, proximity to stream beds or lineaments, permeable subsurface lithology
- **Percolation Tanks:** Good/Moderate GWPZ, flat slope (0–5°), permeable soils (sandy loam)
- **Check Dams:** Moderate slope (2–10°), moderate-high flow accumulation (500–5,000 cells), defined stream channel
- **Bandharas (Tidal Regulators):** Stream mouth at coast, adjacent to vulnerable freshwater extraction zones

The detailed methodology for MAR site suitability analysis, including the proposed 23 structures with their locations and design considerations, is presented in Chapter 5 (Part D: Managed Aquifer Recharge Strategy).

3.8 STEP 7: WATER DEMAND AND WATER STRESS ASSESSMENT

The seventh step involved the quantification of water demand trends, post-monsoon water availability, and water stress conditions.

3.8.1 Water Demand Estimation

Water demand was calculated for four sectors:

- **Domestic Demand:** Population projected from Census of India (2001, 2011) using 1.5% CAGR; per capita demand of 135 LPCD (CPHEEO guidelines)
- **Livestock Demand:** Livestock population projected at 15% decadal growth; water consumption norms as per FAO guidelines (68.25 LPCD for cattle/buffalo, 13.6 LPCD for sheep/goat)

- **Agricultural Demand:** Crop water requirements estimated using FAO-56 methodology; crop areas from LULC classification; irrigation efficiency of 60% considered
- **Tourism Demand:** Estimated using the Equivalent Population Method with 150 LPCD (CPHEEO guidelines)

3.8.2 Water Availability Estimation

Post-monsoon water availability was calculated as:

$$\text{Total Water Available (MLY)} = \text{Groundwater Recharge (ML)} + \text{Dead Storage (ML)}$$

Groundwater recharge was estimated using the Water Table Fluctuation (WTF) method (Healy and Cook, 2002). Dead storage was calculated based on saturated thickness and specific yield.

3.8.3 Water Stress Index (WSI)

The Water Stress Index (WSI) is defined as the ratio of total water demand to total available water resources (UNESCO, 2023; Gain et al., 2022). WSI values were projected for the period 2026–2030 under varying rainfall scenarios.

The detailed methodology for water demand estimation, availability analysis, and WSI computation is presented in Chapter 6 (Water Demand, Availability, and Stress Assessment).

3.9 STEP 8: INTEGRATED WATER RESOURCE DEVELOPMENT PLAN

The eighth step involved the synthesis of all preceding analyses into a practical, phased **Integrated Water Resource Development Plan** for Khadir Island. The plan integrated the findings of groundwater potential assessment, numerical groundwater-flow modelling, seawater-intrusion analysis, managed aquifer recharge planning, and water-demand evaluation to develop sustainable groundwater-management strategies for the island. Particular emphasis was placed on balancing groundwater utilization with natural and enhanced recharge, controlling salinity risks, reducing water demand, and improving long-term water security through a phased implementation framework extending from **2026 to 2035**.

The planning framework was developed using the spatial, hydrogeological and numerical outputs generated during the preceding stages. The groundwater potential assessment was used to identify areas suitable for groundwater development and recharge interventions, while the numerical groundwater-flow and seawater-intrusion assessments provided information on groundwater behaviour, aquifer response and salinity-related constraints. Water-demand and water-stress assessments were subsequently used to establish the requirement for demand-side

management and additional water sources. These outputs were collectively used to formulate the location, priority and sequence of management interventions.

3.9.1 Planning Framework

The plan was developed based on the synthesis of key constraints identified in the hydrogeological assessment, numerical modelling, and water stress analysis. A 10-year planning horizon (2026–2035) was adopted with five implementation phases:

- **Phase 1 (Years 1–2):** Emergency demand management and monitoring expansion
- **Phase 2 (Years 2–4):** Agricultural efficiency and MAR pilot implementation
- **Phase 3 (Years 3–5):** Seawater intrusion control and bandhara construction
- **Phase 4 (Years 4–7):** Palaeochannel exploration and alternative supply development
- **Phase 5 (Years 5–10):** Livelihood integration and long-term sustainability

The sequencing of the phases was designed to provide an adaptive progression from immediate demand management and monitoring, through recharge enhancement and salinity control, to alternative-source development and long-term sustainability planning.

3.9.2 Demand-Side and Supply-Side Interventions

The proposed plan combines **demand-side management** with **supply-side augmentation**. Demand-side interventions target reduction in water consumption, particularly in domestic and agricultural sectors, whereas supply-side interventions focus on increasing effective groundwater recharge and developing supplementary water sources.

A target of **27% overall reduction in water demand across the domestic and agricultural sectors** was adopted as part of the planning framework. On the supply side, proposed **Managed Aquifer Recharge (MAR)** structures were considered for augmenting groundwater availability, with an estimated **90 MLY of additional water supply** under the adopted planning assumptions. Palaeochannel exploration and potential palaeochannel-fed desalination were also considered as supplementary options for addressing future water requirements.

The selection and prioritisation of interventions were based on the combined interpretation of groundwater potential, hydrogeological conditions, modelled groundwater behaviour, seawater-intrusion risk, water demand and site-specific feasibility. The proposed framework therefore does not consider recharge augmentation independently, but links recharge interventions with groundwater protection, demand management and long-term monitoring.

3.9.3 Institutional, Community and Monitoring Framework

Implementation of the proposed plan requires coordination among relevant government agencies, local institutions and the island community. Community participation is particularly important for demand management, agricultural water-use efficiency, protection of recharge structures and reporting of changes in groundwater availability and quality.

A monitoring framework was therefore incorporated into the planning approach to periodically evaluate groundwater levels, groundwater quality, abstraction, recharge performance and seawater-intrusion conditions. The monitoring results can be used to modify the timing, intensity or priority of subsequent interventions. This provides an adaptive management mechanism in which the water-resource development plan can be progressively refined as additional field observations and monitoring data become available.

The detailed institutional arrangements, community participation mechanisms, implementation schedule, performance indicators, and monitoring and evaluation framework are presented in Chapter 8: Integrated Water Resource Development Plan.

3.10 STEP 9: CONCLUSIONS AND RECOMMENDATIONS

The ninth and final step involved the synthesis of key findings, articulation of original contributions to knowledge, and formulation of actionable recommendations for policy makers, water managers, and future researchers.

3.10.1 Synthesis Approach

The ninth and final step involved the synthesis of the key findings obtained from the different analytical components of the study, articulation of the original contributions to knowledge, and formulation of actionable recommendations for policymakers, water-resource managers, local stakeholders, and future researchers. The conclusions were derived by integrating the outcomes of groundwater potential assessment, hydrogeological investigations, numerical groundwater-flow modelling, seawater-intrusion assessment, hydrochemical evaluation, managed aquifer recharge planning, and water-demand and water-stress analysis.

Particular emphasis was placed on establishing the relationship between **groundwater availability, groundwater-flow behaviour, salinity risks, recharge enhancement, water demand, and long-term resource sustainability**. The integrated interpretation of these components provided the basis for evaluating the effectiveness and applicability of the proposed water-resource development strategies for Khadir Island.

Conclusions were drawn from each major analytical component, including:

- groundwater potential zone assessment;
- hydrogeological and field investigations;
- numerical groundwater-flow modelling;
- seawater-intrusion assessment;
- hydrochemical validation;
- MAR site selection and planning; and
- water-demand and water-stress assessment.

The findings from these components were subsequently synthesised to establish the overall groundwater-resource status and management requirements of Khadir Island. The recommendations were formulated at three levels:

1. **Immediate and short-term actions** for groundwater protection, demand management, monitoring and recharge enhancement on Khadir Island;
2. **Policy and management recommendations** for relevant state and central government agencies and water-resource authorities; and
3. **Future research directions**, particularly related to long-term monitoring, improved hydrogeological characterisation, model refinement, climate variability, seawater-intrusion assessment, and post-MAR performance evaluation.

The final conclusions, original contributions, recommendations, and directions for future research are presented in the concluding chapter of the thesis.

3.11 MULTI-LINE VALIDATION FRAMEWORK

Given the sparse long-term groundwater monitoring network on Khadir Island, with only two wells having continuous long-term records, a **multi-line validation and uncertainty assessment framework** was adopted throughout the study to establish confidence in the analytical and numerical outputs. Rather than relying on a single validation criterion, the framework combines numerical model performance, sensitivity analysis, hydrogeochemical evidence, and hydrogeological parameter plausibility.

The framework comprises four complementary lines of evidence:

1. **Water Balance Closure:** The numerical stability and internal consistency of the MODFLOW model were evaluated using the simulated water-budget components and cumulative mass-balance error. The cumulative mass-balance error was maintained at **less than 0.5%**, indicating satisfactory numerical closure of the groundwater-flow model. This criterion was used to confirm that the simulated inflows and outflows were adequately balanced within the numerical model.

2. **Sensitivity and Uncertainty Analysis:** Sensitivity analysis was undertaken by systematically varying key hydrogeological and model parameters to evaluate their influence on simulated groundwater levels and model outputs. Parameters such as **hydraulic conductivity, recharge and other relevant aquifer properties** were examined within plausible ranges. The resulting variation in model outputs was used to identify the parameters exerting the greatest influence on model behaviour and to assess the uncertainty associated with parameter selection. This analysis provides an indication of the robustness of the model results under reasonable variations in input parameters. It also helps identify the parameters for which improved field measurements would provide the greatest benefit for future model refinement.
3. **Hydrogeochemical Validation:** The simulated seawater-intrusion behaviour was evaluated against observed groundwater-quality characteristics from the available monitoring wells. Particular attention was given to **TDS, chloride concentration, and Na⁺/Cl⁻ ratios**, which provide independent hydrochemical evidence of saline influence. The comparison between modelled intrusion behaviour and observed hydrochemical trends was used to assess whether the simulated spatial and temporal patterns were consistent with the available field evidence. This hydrochemical evidence was particularly important because of the limited number of long-term groundwater-level monitoring locations on the island.
4. **Parameter Plausibility:** The calibrated hydrogeological parameters, including **hydraulic conductivity, specific yield and recharge percentage**, were evaluated against published values and ranges reported for comparable aquifer systems in the Kachchh region and other relevant hydrogeological environments. References including **CGWB (2016), Scanlon et al. (2006), and Freeze and Cherry (1979)** were considered in assessing the physical plausibility of the selected parameters. This comparison ensured that the calibrated parameter values were not considered solely on the basis of numerical model fit, but were also examined for their consistency with known hydrogeological conditions.

3.11.1 Integration of Validation Evidence

The four components were interpreted collectively rather than treating any single criterion as definitive. **Water-balance closure** provided a check on numerical consistency, **sensitivity analysis** provided information on parameter influence and uncertainty, **hydrogeochemical observations** provided field-based evidence for saline conditions, and

parameter plausibility provided an independent hydrogeological basis for evaluating the calibrated model parameters.

Accordingly, the reliability of the model outputs was assessed through **converging evidence from numerical, statistical, hydrogeological and hydrochemical perspectives**. This approach is particularly appropriate for Khadir Island because the limited long-term monitoring network prevents conventional validation based solely on a large number of continuous observation wells.

Nevertheless, the adopted framework does not eliminate uncertainty. Uncertainty remains associated with the spatial distribution of hydraulic properties, recharge estimation, abstraction data, boundary-condition representation, limited monitoring observations and the conceptual simplifications inherent in numerical modelling. The results are therefore interpreted within these limitations, and the proposed framework allows future monitoring data to be incorporated for subsequent model refinement and reassessment.

Table No 3.3: Summary of the Multi-Line Validation Framework

Validation / Assessment Component	Evidence Used	Purpose
Water Balance Closure	MODFLOW mass-balance error <0.5%	Check numerical consistency and water-budget closure
Sensitivity & Uncertainty Analysis	Variation of key model parameters	Identify influential parameters and assess uncertainty
Hydrogeochemical Validation	TDS, Cl ⁻ and Na ⁺ /Cl ⁻ observations	Corroborate simulated saline-intrusion behaviour
Parameter Plausibility	Calibrated K, specific yield and recharge compared with published ranges	Assess physical realism of calibrated parameters

3.12 SUMMARY OF CHAPTER 3

This chapter has presented the comprehensive **nine-step methodological framework** developed for the hydrogeological assessment and sustainable groundwater management of Khadir Island. The methodology integrates remote sensing, GIS, hydrogeological

investigations, numerical modelling, hydrochemical assessment, managed aquifer recharge, water-demand analysis, and integrated water-resource planning.

The major methodological steps are summarised as follows:

1. **Data Collection and Database Preparation:** Compilation of satellite imagery, geological maps, hydro-meteorological data, groundwater information, and socio-economic data into a unified geospatial database.
2. **RS-GIS Processing and Thematic Layer Preparation:** Pre-processing of multi-sensor satellite data and preparation of **eight thematic layers** for groundwater potential assessment.
3. **Groundwater Potential Zoning (GWPZ):** Application of the **Multi-Influencing Factor (MIF)** method to integrate the thematic layers and classify the island into **Good, Moderate, and Poor groundwater potential zones**.
4. **Numerical Groundwater-Flow Modelling (MODFLOW-6):** Development of a **transient three-dimensional groundwater-flow model with four hydrostratigraphic layers** for the period **2001–2020**, incorporating the defined aquifer properties, recharge conditions, abstraction and boundary conditions.
5. **Seawater-Intrusion Assessment (SWI2):** Simulation of seawater-intrusion dynamics and saline-interface behaviour, supported by available hydrochemical observations for validation.
6. **Managed Aquifer Recharge (MAR) Site Selection:** Application of multi-criteria assessment to identify **23 suitable locations** for recharge shafts, percolation tanks, check dams and bandharas.
7. **Water Demand and Water Stress Assessment:** Quantification of sectoral water-demand trends for **2001–2041**, assessment of post-monsoon water availability, and projection of the **Water Stress Index (WSI) for 2026–2030**.
8. **Integrated Water Resource Development Plan:** Synthesis of the analytical findings into a **five-phase, 10-year implementation framework (2026–2035)** incorporating demand-side management, groundwater protection, recharge enhancement, salinity control and supplementary water-resource development.

9. **Conclusions and Recommendations:** Consolidation of the major findings, original contributions to knowledge, management implications, and recommendations for policymakers, water-resource managers and future research.

In addition to these nine methodological steps, a **multi-line validation and uncertainty assessment framework** was incorporated to evaluate the reliability and robustness of the analytical and numerical outputs under the data-scarce conditions of Khadir Island. The framework considered **water-balance closure, sensitivity and uncertainty analysis, hydrogeochemical evidence, and hydrogeological parameter plausibility**. This approach provided converging evidence for assessing the model outputs while recognizing uncertainties associated with recharge estimation, hydraulic parameters, boundary conditions, abstraction data and limited long-term monitoring observations.

Overall, the integrated methodology establishes a systematic linkage between **groundwater potential assessment, hydrogeological characterisation, groundwater-flow modelling, seawater-intrusion assessment, hydrochemical validation, MAR planning, water-demand assessment and long-term water-resource development**. This provides the scientific and methodological foundation for the results and discussions presented in the subsequent chapters.

CHAPTER 4:

STUDY AREA AND FIELD INVESTIGATIONS: KHADIR ISLAND, GREAT RANN OF KACHCHH

"The Great Rann of Kachchh and Khadir Island: a hyper-saline landscape,
its people, and its water challenges"

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4.1 Introduction

This chapter provides a comprehensive description of the study area, with primary emphasis on Khadir Island, the largest and most populated inhabited bet (island) within the Great Rann of Kachchh (GRK), Gujarat, western India. Owing to the similar hydrological, environmental, and socio-economic characteristics shared among the inhabited islands of the GRK, the broader regional context of Bela Island, Chorar Island, and the adjoining Banni grasslands is also discussed wherever relevant information is available. The chapter establishes the physical and hydrogeological setting necessary for understanding the groundwater conditions, water scarcity issues, and resource management challenges prevailing in this hyper-arid island environment.

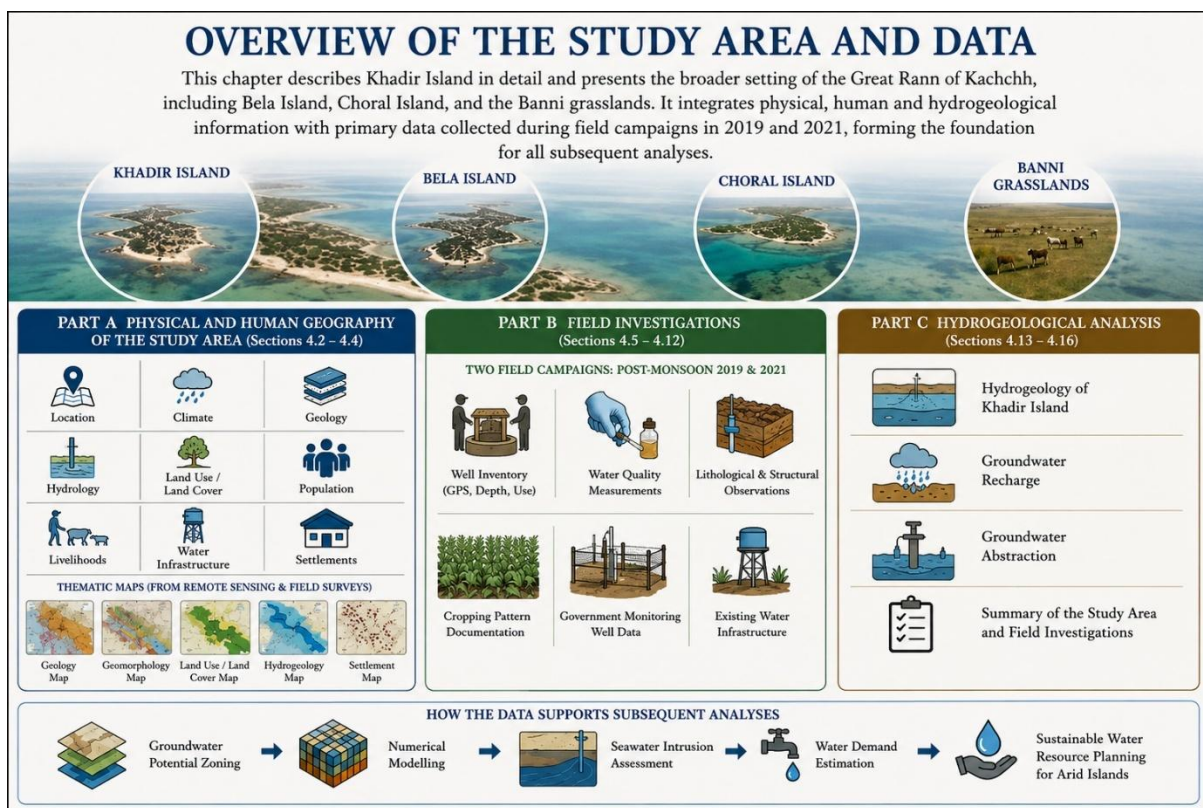


Figure 4.1: Overview of the Study Area

The chapter is organised into three major parts. Part A (Sections 4.2–4.4) describes the physical and human geography of the study area, including the regional setting of the Great Rann of Kachchh, the geographical and environmental characteristics of Khadir Island, and the preparation and interpretation of thematic layers derived from remote sensing, GIS analysis, and field observations. These thematic layers form the spatial foundation for subsequent hydrogeological investigations and groundwater assessment.

Part B (Sections 4.5–4.12) presents the detailed field investigations conducted during systematic post-monsoon surveys carried out in 2019 and 2021. These investigations include

well inventory surveys, groundwater quality measurements, lithological and structural observations, cropping pattern documentation, government monitoring well data collection, and assessment of existing water infrastructure across Khadir Island. The field data generated through these investigations provide the primary database for analysing groundwater occurrence, recharge conditions, abstraction patterns, and water resource stress within the study area.

Part C (Sections 4.13–4.16) focuses on the hydrogeological analysis of Khadir Island, including the characteristics of aquifers, groundwater recharge conditions, and groundwater abstraction patterns. This section integrates field observations with thematic and hydrogeological analyses to develop a comprehensive understanding of groundwater behaviour in the island environment. The chapter concludes by summarising the significance of the study area and field investigations as essential inputs for subsequent analyses, including groundwater potential zoning, managed aquifer recharge assessment, numerical groundwater modelling, seawater intrusion studies, and water demand estimation for sustainable water resource development planning.

PART A: PHYSICAL AND HUMAN GEOGRAPHY OF THE STUDY AREA

4.2 THE GREAT RANN OF KACHCHH: A HYPER-SALINE LANDSCAPE

4.2.1 Geographic Extent and Physiography

The Great Rann of Kachchh is a vast, seasonal salt desert located in the Kachchh district of Gujarat, western India. It extends between latitudes 23°40'N to 24°40'N and longitudes 69°30'E to 71°00'E, covering an area of approximately 18,000 km² (Maurya et al., 2013). To the north, it is bounded by the Nagar Parker Fault and the Sindh province of Pakistan; to the south by the Kachchh mainland and the Banni grasslands; to the west by the Arabian Sea; and to the east by the Little Rann of Kachchh.

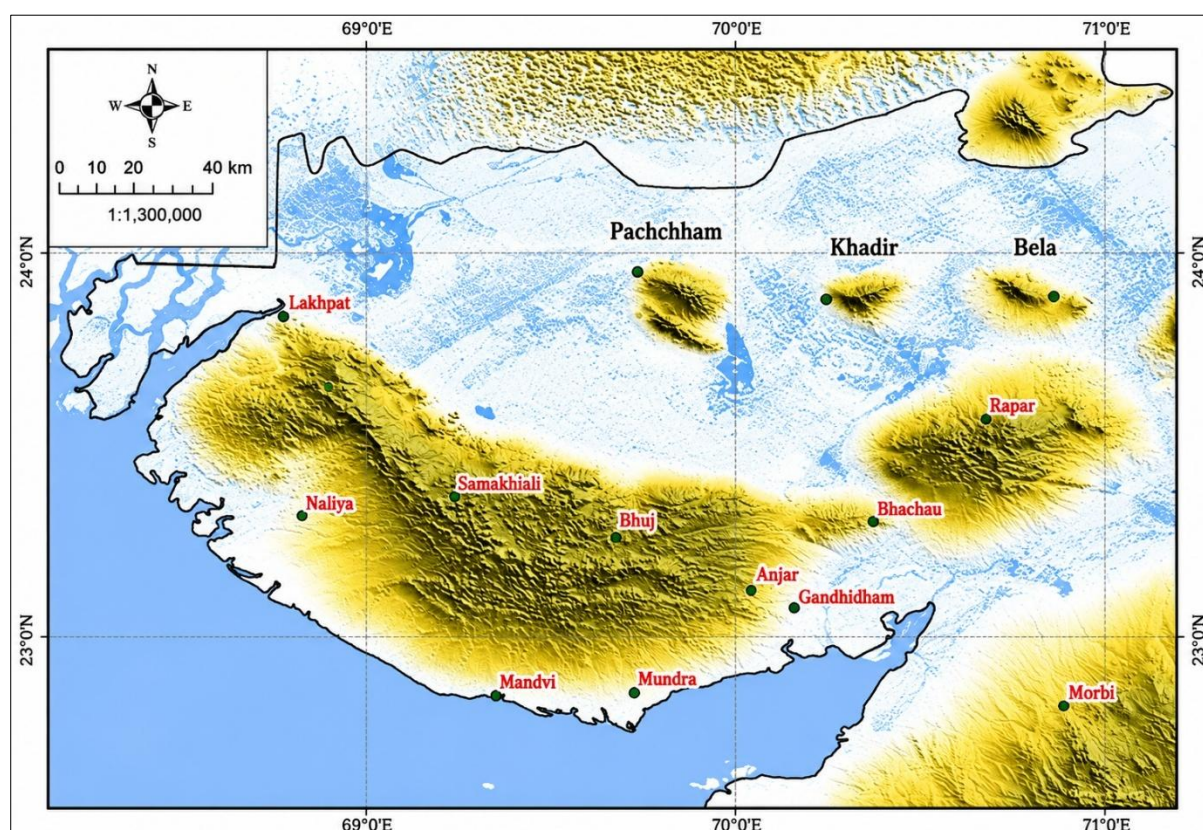


Figure-4.2: Island Belt along with the Great Rann of Kutch-Gujarat

The Rann is not a single, uniform landscape but a mosaic of different landforms. During the monsoon (June to September), the Rann is inundated by seawater that enters through the Gulf of Kachchh and by freshwater runoff from the surrounding highlands. The water depth

is generally less than one metre, and the inundation can extend for tens of kilometres inland. During the dry season (October to May), the water evaporates, leaving behind a white, cracked crust of salt and clay. This seasonal cycle—inundation followed by desiccation—has been ongoing for thousands of years, shaping the unique geochemistry and ecology of the region.

The elevation of the Rann floor is only a few metres above mean sea level. The lowest parts, which remain waterlogged for longer periods, are often below the level of the surrounding high tides, allowing seawater to enter even outside the monsoon *season* (Glennie and Evans, 1976).

4.2.2 The Bets: Islands of Elevation

Scattered across the Great Rann of Kachchh are several elevated landmasses locally known as *bets* or islands, which remain above the seasonal inundation levels of the surrounding salt flats. These islands vary considerably in size, elevation, and geomorphological characteristics, ranging from relatively flat terrains to rugged uplands with prominent escarpments and steep northern slopes. Major islands include **Pachchham, Khadir, Bela, and Chorar**, along with several smaller islands that support seasonal grazing and dispersed settlements. Among these, **Pachchham Island** is the largest and contains **Kalo Dungar (Black Hill)**, the highest peak in the Kachchh region, rising to approximately 462 m above mean sea level. **Khadir Island**, although smaller than Pachchham, is of exceptional archaeological, socio-economic, and hydrogeological significance owing to the presence of the UNESCO World Heritage Site of Dholavira and its dependence on limited freshwater resources. These elevated islands form distinct geomorphic units within the Great Rann and provide the only permanently habitable landscapes within an otherwise extensive saline environment.

The most significant bets, from largest to smallest, are:

- **Pachchham Island:** Pachchham Island is the largest island (bet) of the Great Rann of Kachchh, covering approximately 790 km². The island is characterized by rugged topography, elevated plateaus, steep escarpments, and hill ranges. It contains Kalo Dungar (Black Hill), the highest peak in Kachchh, rising to about 462 m above mean sea level. Owing to its unique geomorphology, ecological significance, and cultural heritage, Pachchham Island represents one of the most prominent landscape features within the Great Rann of Kachchh.

- **Khadir Island:** Approximately 315 km², located in the eastern part of the GRK. It is the largest and most densely populated bet, containing ten villages and the UNESCO World Heritage site of Dholavira.
- **Bela Island:** Approximately 110 km², located immediately west of Khadir Island. It is separated from Khadir by a narrow, seasonally flooded channel. Bela has several villages and is known for its rich fossil deposits.
- **Chorar Island:** A smaller bet, approximately 25 km², located further west. It is less populated and has limited infrastructure.
- **Numerous smaller bets:** Dozens of very small elevated patches, many of which are uninhabited or used only for seasonal grazing.

These bets are not true islands in the sense of being surrounded by open water throughout the year. Rather, they are "islands" in the sense that they are completely surrounded by the saline Rann floor, which is either flooded or salt-encrusted, and are isolated from the mainland and from each other except by unpaved roads that become impassable during the monsoon.

4.2.3 Rationale for Selecting Khadir Island as the Primary Study Area

Among all the bets of the Great Rann of Kachchh, Khadir Island was selected as the primary study area for this research based on several compelling scientific and practical considerations.

- First, Khadir is the largest bet in the GRK, with an area of approximately 315 km², making it the most significant in terms of both physical extent and water resource potential. As the largest landmass, it hosts the greatest diversity of hydrogeological settings—ranging from alluvial plains in the west to structural hills in the east—providing a comprehensive natural laboratory for testing the integrated geo-hydrological framework proposed in this thesis.
- Second, Khadir Island supports the largest population among all the bets, with approximately 17,000 residents distributed across ten villages. This population depends almost entirely on groundwater for domestic, agricultural, and livestock needs, making the island a high-priority target for water resource assessment and management planning. The presence of the UNESCO World Heritage Site at Dholavira further amplifies the importance of ensuring water security, as tourism continues to grow and place additional demands on the already strained aquifer system.

- Third, despite its size and population, Khadir Island suffers from an acute scarcity of hydrogeological data. Only two long-term government monitoring wells (KC-13 at Dholavira and HPIL_KCH_006 at Kalyanpar) exist on the entire island, and no prior systematic groundwater potential mapping, numerical flow modelling, or seawater intrusion assessment had been conducted before this study. This data-scarcity, while posing methodological challenges, also presents an opportunity to develop and demonstrate a robust, multi-line validation framework that can be replicated in similarly data-poor settings across the GRK and beyond.
- Fourth, the island encapsulates the full spectrum of water-related challenges facing all GRK bets: inherent aquifer salinity from marine sediments, active seawater intrusion, extreme climatic variability, temporal mismatch between monsoon recharge and year-round demand, inefficient agricultural water use, and limited institutional capacity for water management. By addressing these interconnected challenges on Khadir Island, the research develops solutions that are directly transferable to Bela, Chorar, and the smaller inhabited bets with minimal modification.
- Finally, practical considerations of accessibility and logistical feasibility further supported the selection of Khadir Island as the study area. The island is well connected to the mainland through road networks on both its eastern and western sides, providing reliable year-round access for field investigations and monitoring activities. This accessibility facilitated the systematic field campaigns conducted during 2019 and 2021 and enabled comprehensive hydrogeological, hydrochemical, and geospatial data collection. In addition, the presence of existing water management infrastructure—including the Harappan reservoirs at Dholavira, check dams, village ponds, and Holiya recharge structures—provided valuable baseline information and reference points for field validation. Consequently, Khadir Island represents an ideal and strategically important natural laboratory for developing, testing, and demonstrating an integrated approach to sustainable groundwater management for the isolated islands (bets) of the Great Rann of Kachchh.

4.3 KHADIR ISLAND: THE PRIMARY STUDY AREA

4.3.1 Location and Boundaries

Khadir Island lies between latitudes 23°45'N and 24°00'N, and longitudes 70°15'E and 70°45'E. It is situated in the eastern part of the Great Rann of Kachchh, approximately 120 km by road from Bhuj, the district headquarters. The island is roughly oval in shape, with its

long axis-oriented northeast-southwest. The total land area, as measured from satellite imagery, is approximately 315.2 km².

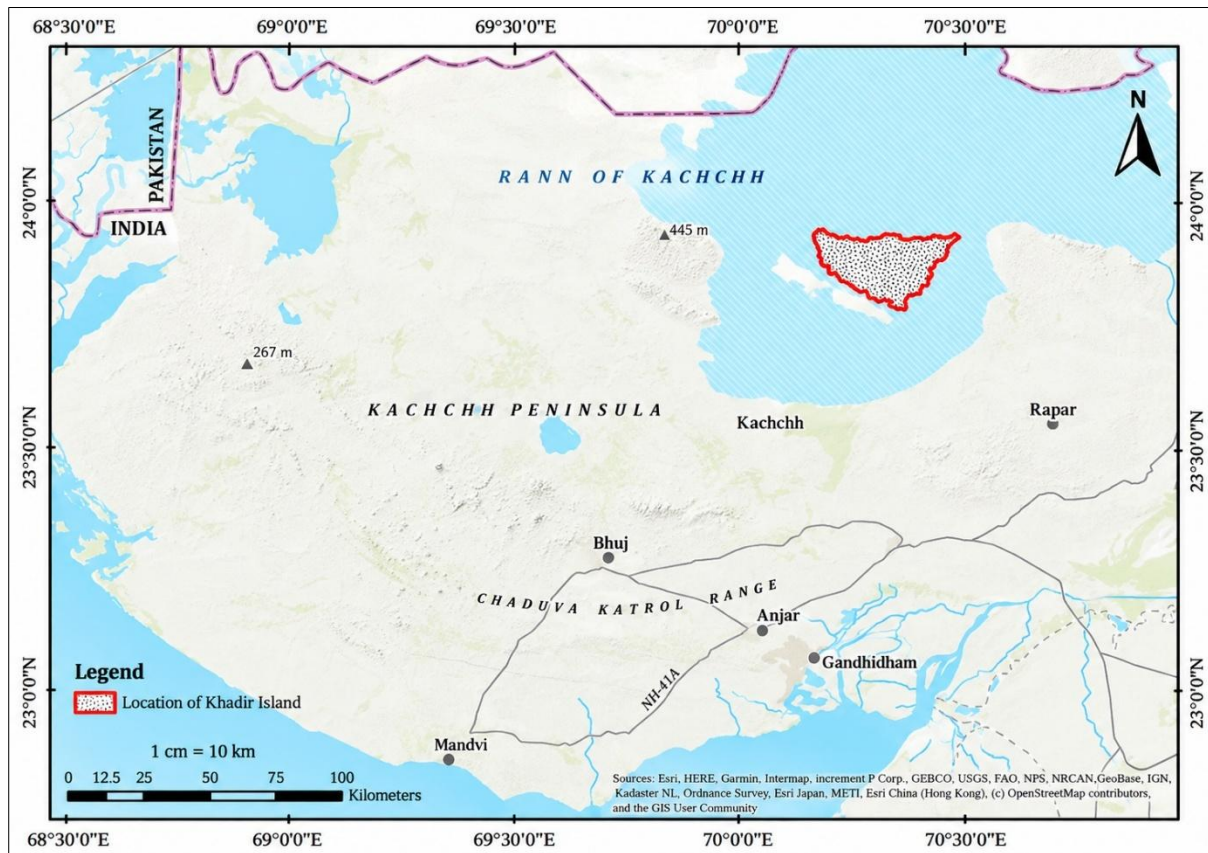


Figure 4.3: Location of Khadir Island in the GRK, Gujarat

The boundaries of the island are defined by the transition from the elevated, relatively flat surface of the bet to the surrounding Rann floor. This transition is often marked by a low scarp or a zone of salt-tolerant vegetation. During the dry season, the boundary is clearly visible as a line where the white salt crust gives way to brown or grey soil with sparse vegetation.

4.3.2 Population and Settlement Pattern of Island:

The spatial distribution of population across Khadir Island reveals significant variation in settlement density, which has important implications for water resource management. The total population of the island is 17,257, distributed across ten villages with an average density of 54.7 persons per km². However, this average masks considerable intra-island variability. Gadhada, located in the eastern part of the island, exhibits the highest population density at 200 persons per km² with a population of 5,590, making it the most populous and densely settled village on the island. This very high density indicates significant population pressure and correspondingly high-water demand concentrated in a relatively small area of 27.95 km². Kalyanpar, also in the eastern sector, shows the second highest density at

82.6 persons per km² with 1,567 residents, reflecting relatively high demographic pressure in this part of the island.

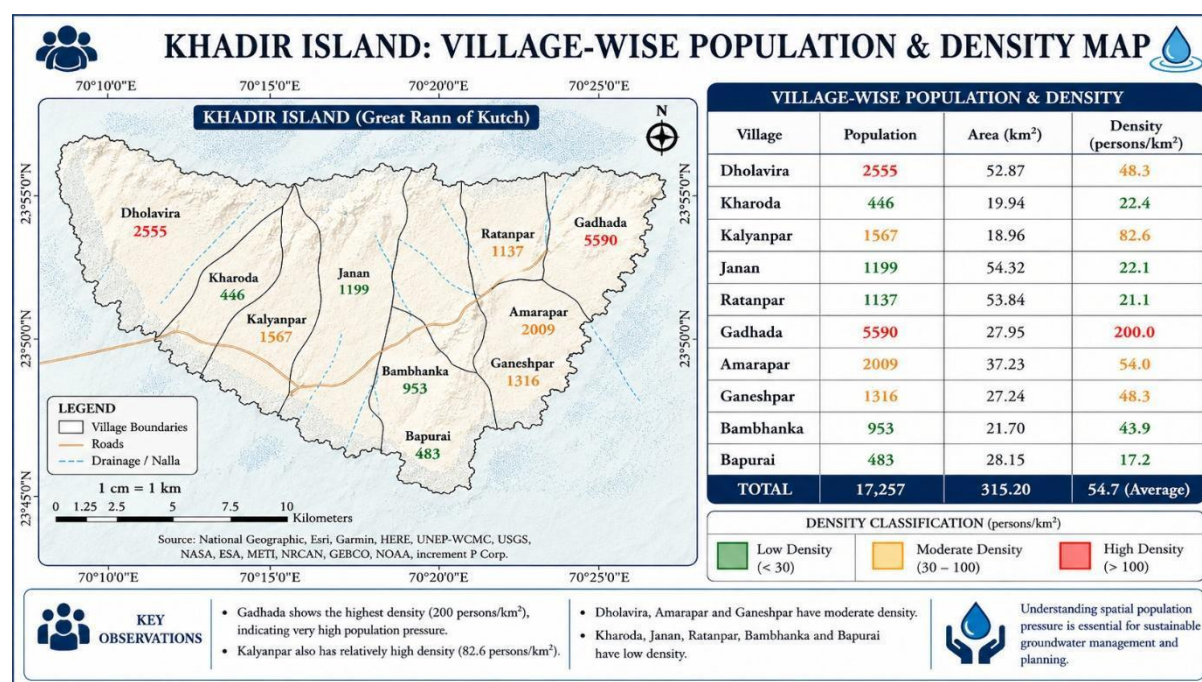


Figure 4.4: Density wise Village Map of Khadir Island

The moderate density category (30–100 persons per km²) includes Dholavira, Amrapar, and Ganeshpar. Dholavira, with 2,555 people distributed across 52.87 km², has a density of 48.3 persons per km². As the location of the UNESCO World Heritage Site, Dholavira experiences additional transient population pressure from tourism, which is not captured in the resident population figures. Amrapar, with 2,009 residents and an area of 37.23 km², has a density of 54.0 persons per km², while Ganeshpar, with 1,316 people in 27.24 km², has a density of 48.3 persons per km². These moderate-density villages represent a balanced human-footprint where water demand, while substantial, is more evenly distributed across the available land area.

The low-density category (<30 persons per km²) comprises Kharoda (446 people, 19.94 km², density 22.4), Janan (1,199 people, 54.32 km², density 22.1), Ratanpar (1,137 people, 53.84 km², density 21.1), Bambhanka (953 people, 21.70 km², density 43.9), and Bapurai (483 people, 28.15 km², density 17.2). These villages, predominantly located in the western and southwestern parts of the island, have relatively larger land areas and smaller populations, resulting in lower water demand per unit area. This dispersed settlement pattern reduces localised pressure on groundwater resources, although the overall water balance of the island remains stressed due to the aquifer's limited storage capacity and the island-wide nature of the seawater intrusion threat.

Understanding this spatial population distribution is essential for sustainable groundwater management and planning. The high-density eastern villages of Gadhada and Kalyanpar, which also happen to lie within the Poor groundwater potential, face the most severe water stress. In contrast, the low-density western villages of Ratanpar and Janan, situated in the Good groundwater potential zone, have greater per capita water availability and represent priority areas for managed aquifer recharge interventions. This spatial correlation between population density and groundwater potential forms a critical input for the Integrated Water Resource Development Plan.

The villages are scattered across the island, with no single dominant urban centre. Dholavira is the most well-known due to the archaeological site, but Gadhada and Amrapar are larger in terms of population and economic activity. Most villages have a primary school, a panchayat office, and one or two small shops. Healthcare facilities are minimal; there is a primary health centre (PHC) in Dholavira, but residents of other villages must travel there or to Bhuj for more serious medical needs. Roads are unpaved in many areas, becoming impassable during the monsoon (Dey and Mandal, 2024).

4.3.3 Livelihoods of Khadir Island:

The livelihoods of Khadir Island are closely linked with the fragile ecological and hydrogeological conditions of the Great Rann of Kachchh. Due to the arid climate, saline environment, and limited freshwater availability, local communities have traditionally developed adaptive livelihood systems based on pastoralism, handicrafts, seasonal agriculture, and tourism. Groundwater availability plays a critical role in sustaining all major livelihood activities across the island (Maurya et al., 2013; IMD, 2022).

4.3.3.1 Pastoralism

Pastoralism is the traditional and dominant livelihood activity on Khadir Island and throughout the Banni and Rann regions. The Muslim Maldhari communities, traditionally known as livestock keepers, constitute the major pastoral population of the region. These communities are organized into several clans including Raysipotra, Halepotra, Hingorja, Node, Sumra, Sameja, Mutwa, Jat, and Bhamba. The local population primarily speaks Kachchhi in Sindhi dialect, reflecting historical socio-cultural connections with the Sindh region (Government of Gujarat, 2021).

The region is well known for its indigenous livestock breeds such as the Banni buffalo, Kankrej cattle, Sindhi horse, Kachchhi goat, and Kachchhi camel. These breeds are

highly adapted to arid climatic conditions, saline environments, and limited water availability (India Water Portal, 2024).

Pastoral communities practice seasonal migration depending upon fodder and water availability, particularly during drought years and prolonged dry seasons. More than 93% of households in the Banni region are directly or indirectly associated with pastoralism and dairy enterprise, contributing significantly to the regional economy (India Water Portal, 2024). Groundwater availability strongly influences livestock sustainability because drinking water for both humans and animals primarily depends on groundwater resources.

4.3.3.2 Handicrafts and Traditional Occupations

Traditional handicrafts constitute another important livelihood activity on Khadir Island. Communities such as Meghwal and Vadha Koli possess rich traditions of embroidery, leatherwork, wood carving, textile decoration, and construction of traditional circular mud houses locally known as *bhungas* (Government of Gujarat, 2021).

Women play an important role in embroidery and textile-related activities, contributing significantly to household income generation. Handicraft products are marketed locally as well as through tourism networks, thereby supporting rural livelihoods in areas where agricultural opportunities remain limited due to salinity and climatic constraints (UNESCO, 2021).

Traditional occupations also include animal husbandry services, salt-related activities, small-scale trade, and transportation. However, many of these occupations remain seasonal and economically vulnerable due to environmental uncertainties and fluctuating tourism demand.

4.3.3.4 Tourism

Tourism has emerged as an increasingly important economic sector in the Great Rann of Kachchh during recent decades. The scenic salt desert landscape, cultural heritage, handicrafts, wildlife, and archaeological significance of Dholavira attract substantial tourist inflow to the region. Tourism activity is concentrated mainly during the winter season from November to February when climatic conditions are relatively favourable (UNESCO, 2021). The inscription of Dholavira as a UNESCO World Heritage Site in 2021 significantly increased tourist footfall on Khadir Island. In addition, the annual Rann Utsav cultural festival attracts large numbers of domestic and international visitors every year (Government of Gujarat, 2022). Tourism generates employment opportunities in the form of tourist guides, transport operators, hotel staff, restaurant workers, handicraft sellers, and local service providers. However, the

tourism sector is highly seasonal and exerts additional pressure on groundwater resources because freshwater demand increases considerably during the tourist season. Sustainable groundwater management is therefore essential for maintaining long-term tourism sustainability on the island (IMD, 2022).

4.3.3.5 Agriculture and Crop Patterns

Agriculture on Khadir Island is constrained by low and erratic rainfall, saline groundwater conditions, poor soil quality, and high evapotranspiration rates. Nevertheless, agriculture remains an important supplementary livelihood activity for local communities. Approximately 34% of the land area is used for agricultural purposes, mainly during favourable monsoon years (IMD, 2022).

The principal crop cultivated in the region is bajra (*Pennisetum glaucum*), a drought-resistant cereal crop well adapted to arid climatic conditions, saline soils, and limited water availability. In recent years, farmers have also cultivated crops such as cumin, coriander, mustard, castor, fodder crops, and seasonal vegetables in areas where groundwater quality permits irrigation (Government of Gujarat, 2021).

Agricultural productivity remains highly vulnerable to rainfall variability and increasing groundwater salinity. Crop failure during drought years is common, forcing many households to depend more heavily on livestock rearing and non-agricultural occupations. Groundwater quality and groundwater availability therefore directly influence agricultural sustainability on the island (Maurya et al., 2013).

A traditional livelihood practice that is gradually being revived is the cultivation of piloodi (*Salvadora persica*), a salt-tolerant tree species adapted to saline environments. The seeds of piloodi yield kardi oil, which is used in cosmetic and medicinal products. Local organizations such as Preservation and Proliferation of Art and Culture (PAG) are encouraging plantation and conservation of piloodi as a sustainable livelihood option suited to the saline ecological conditions of the Great Rann of Kachchh (IRMA, undated).

Overall, the livelihoods of Khadir Island are highly dependent on groundwater resources and environmental stability. Any deterioration in groundwater quantity or quality directly affects pastoralism, agriculture, tourism, and domestic water security. Sustainable water resource management is therefore essential for ensuring long-term livelihood resilience and socio-economic sustainability within the study area. Given the island's arid climate, limited freshwater availability, and increasing water demand, the implementation of integrated water resource management strategies is critical for balancing resource utilization with

environmental conservation. Strengthening groundwater recharge, improving water-use efficiency, and protecting freshwater resources from salinity intrusion will play a vital role in enhancing the adaptive capacity of local communities and securing sustainable livelihoods for future generations.

4.4 PREPARATION AND CONSIDERATION OF THEMATIC LAYERS

The preparation of thematic layers constitutes an essential component of groundwater potential assessment and integrated geo-hydrological analysis. Thematic layers represent the spatial distribution of hydrogeological, geomorphological, climatic, and environmental parameters that influence groundwater occurrence, recharge, storage, and movement within the study area. In the present study, thematic layers were prepared using remote sensing data, GIS techniques, digital elevation models, and published geological and hydrological datasets.

A total of eight thematic layers were considered for groundwater potential zoning and hydrogeological evaluation of Khadir Island. These include lithology, geomorphology, lineament density, rainfall, slope, drainage density, land use/land cover (LULC), and soil type. Each thematic layer was prepared using authenticated national and international datasets integrated within the ArcGIS 10.8 environment.

The thematic layers were selected based on their direct influence on groundwater recharge, infiltration characteristics, runoff generation, aquifer permeability, and groundwater storage potential. Multi-source satellite imagery, DEM datasets, and geological information were systematically processed to generate spatially consistent thematic maps suitable for groundwater modelling and groundwater potential analysis.

4.4.1 Topography and Drainage

The topography of Khadir Island is gently undulating, with elevations ranging from approximately 0 metres above mean sea level (amsl) along the coastal margins to about 267 metres amsl along a central-north ridge. The Digital Elevation Model (DEM) of the island, derived from SRTM data, reveals a clear topographic gradient: the island exhibits a gentle slope from the central–north ridge towards the coastal margins in all directions. The highest elevation point, reaching approximately 267 metres, is located in the central-northern part of the island and acts as a groundwater divide, separating flow paths that drain westward, southward, and eastward towards the surrounding Rann. The lowest elevations, approaching sea level, occur

along the western, southern, and eastern margins where the island transitions into the saline mudflats of the Great Rann of Kachchh.

This topographic configuration has profound hydrogeological implications. Elevation controls surface runoff direction towards coastal and depression zones. The central-north ridge forms the primary topographic high, and the gently sloping terrain towards the coast favours runoff convergence in lower elevation zones. Lower elevation areas, particularly in the western and southern parts of the island, have higher potential for water accumulation and recharge, as surface runoff naturally converges towards these depressions during monsoon rainfall events. Conversely, the higher central ridge areas generate runoff that flows radially outward, contributing to recharge in the peripheral lowlands.

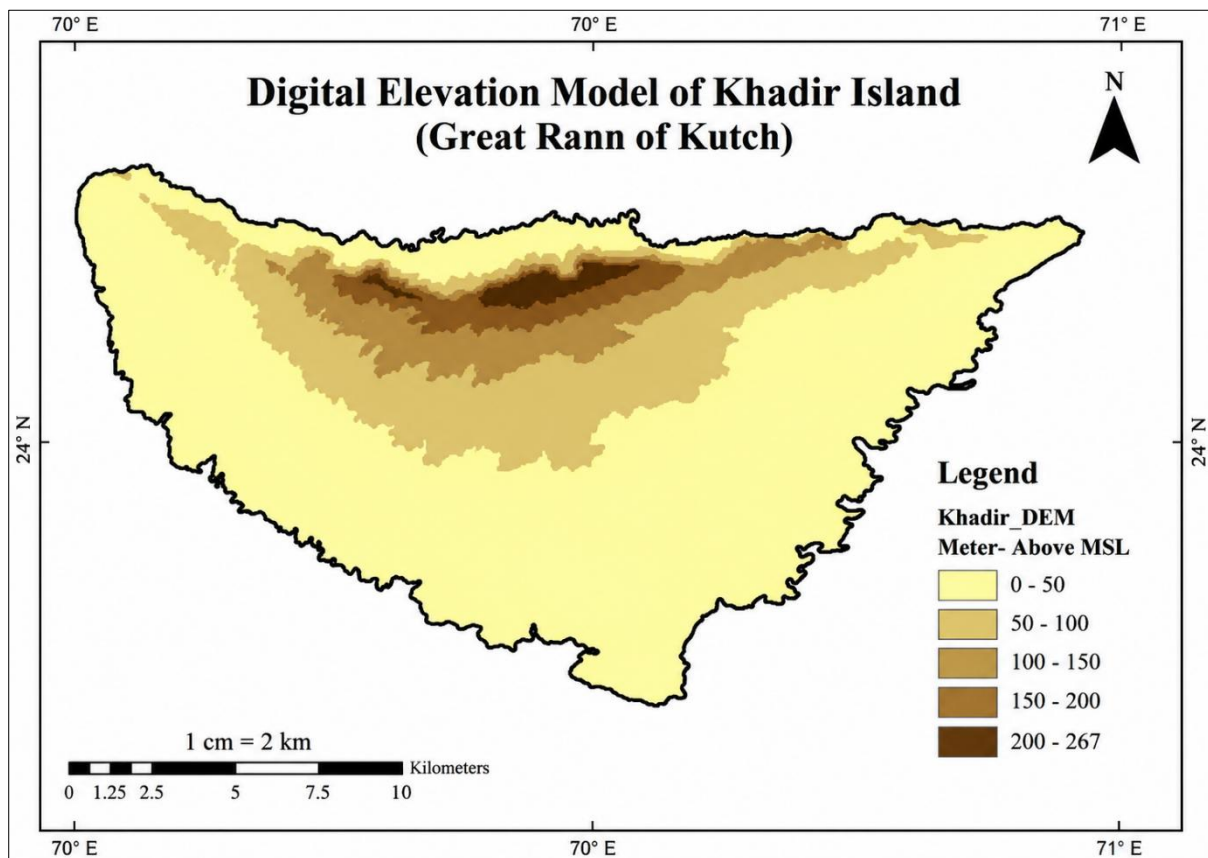


Figure 4.5: Digital Elevation Model of Khadir Island (Source: SRTM DEM)

4.4.1.1 Drainage Network Characteristics

The drainage network on Khadir Island is dendritic to sub-dendritic in nature, a pattern that reflects the underlying lithological and structural controls on surface water flow. The dendritic pattern, characterised by irregular branching of tributaries in many directions, indicates a gentle slope in the western and central parts of the island, where the terrain is nearly

level and surface water moves slowly, allowing for greater infiltration. In the eastern part, the drainage pattern transitions to a more sub-dendritic form, reflecting the moderately steeper terrain and structural influences from faults and fractures.

The drainage network is composed entirely of ephemeral streams that flow only during and immediately after rainfall events. These streams, locally called *nallas*, range from 1st to 4th order, indicating a moderately developed drainage system. First and second-order streams originate in the higher eastern and central areas, where steeper slopes generate rapid runoff. These smaller tributaries coalesce into third and fourth-order channels as they flow westward and southward, eventually discharging into the surrounding Rann.

The drainage density is moderate, reflecting the balance between infiltration and runoff in this arid environment. Areas of lower drainage density, predominantly in the western and central parts, indicate higher infiltration capacity, as a greater proportion of rainfall percolates into the subsurface rather than contributing to surface flow. Areas of higher drainage density, particularly in the eastern part, indicate lower permeability and greater runoff generation. The flow direction is radial to centripetal, with streams originating from the central-north topographic high and flowing outward in all directions towards the island margins.

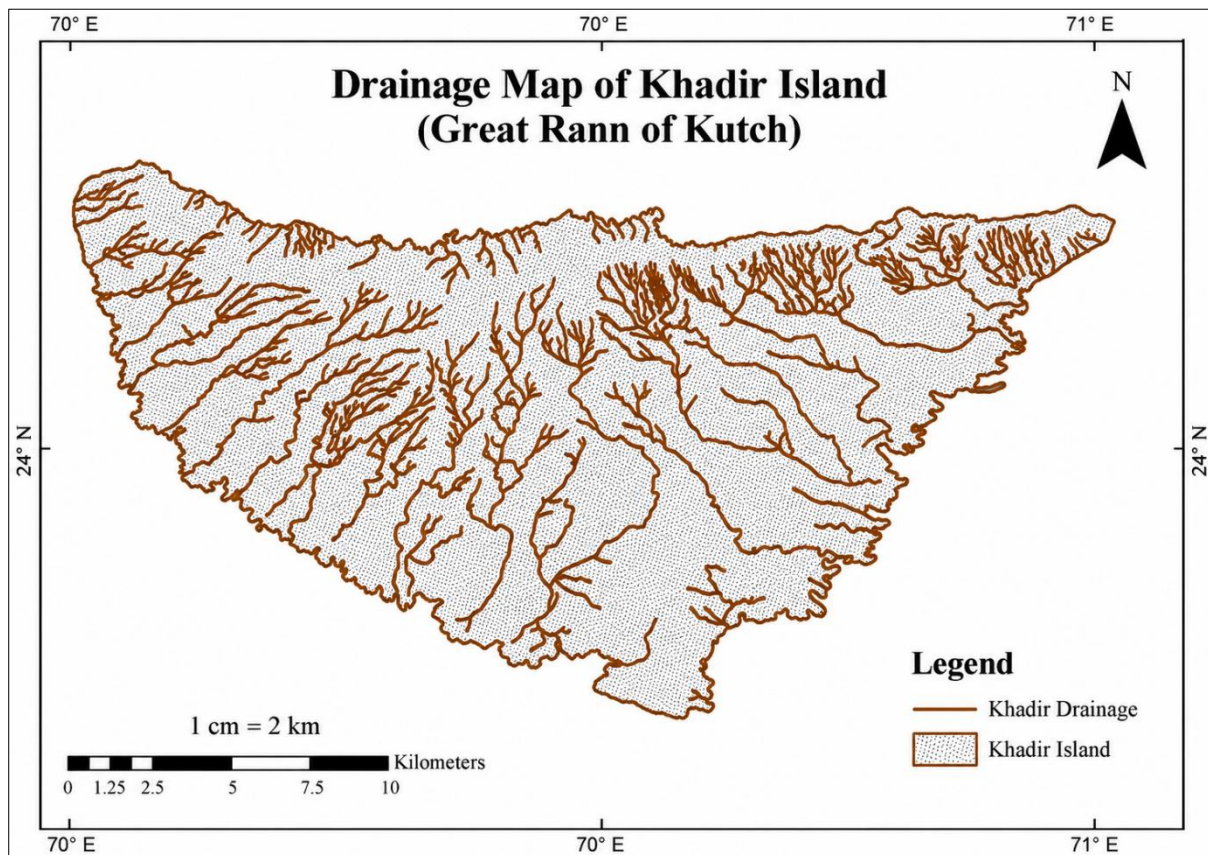


Figure 4.6: Drainage Map of Khadir Island (Source: Derived from SRTM DEM)

4.4.1.2 Slope Analysis and Infiltration Potential

The slope characteristics of Khadir Island, derived from the SRTM DEM, further refine the understanding of recharge and runoff dynamics. The slope map classifies the island into five distinct categories, each with different implications for groundwater recharge as shown in figure 4.7:

- **Nearly Level (0–2°):** This slope class occupies the western and central parts of the island. These areas represent the primary groundwater recharge zones, as the flat terrain promotes ponding of monsoon rainfall and maximises the residence time of water at the surface, allowing for greater infiltration. The nearly level terrain, combined with the sandy clay loam soils that dominate this region, creates favourable conditions for vertical percolation.

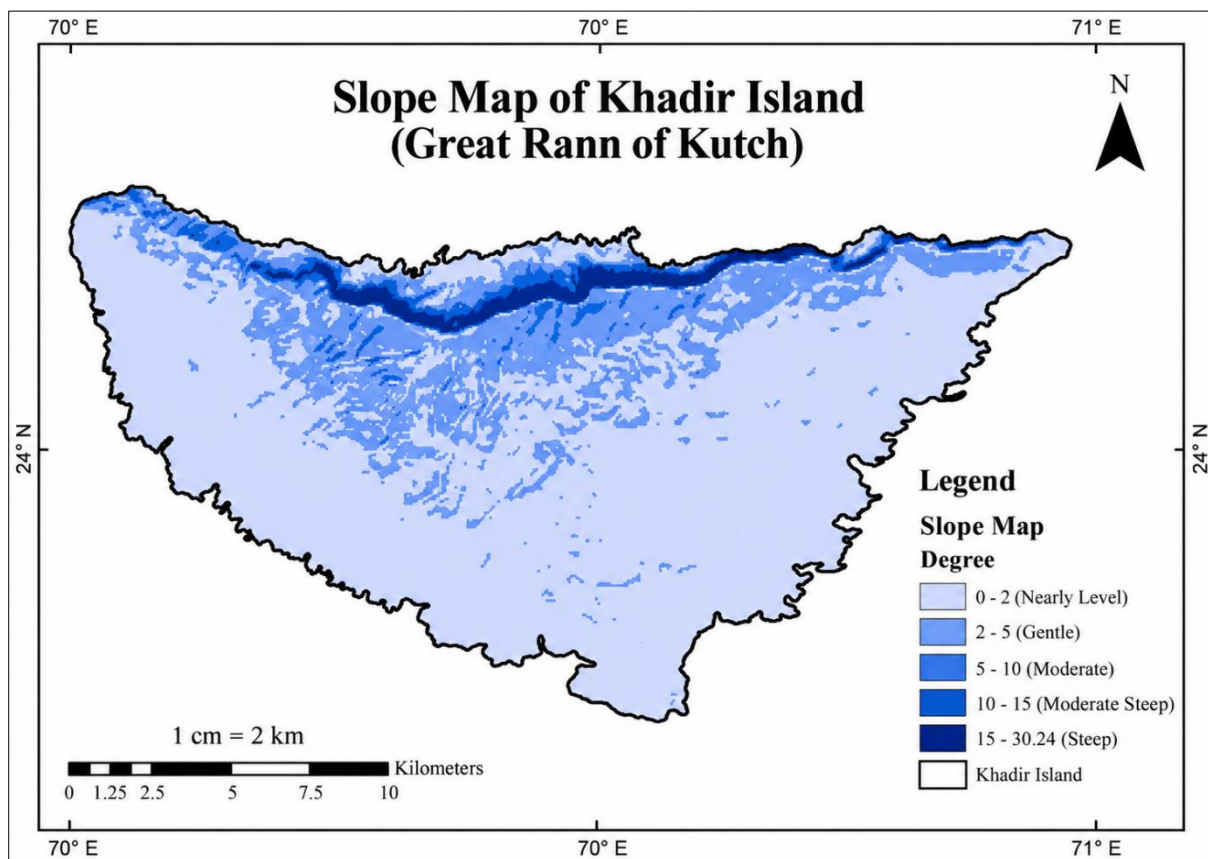


Figure 4.7: Slope Map of Khadir Island (Source: Derived from SRTM DEM)

- **Gentle (2–5°):** This class occurs in the transition zone between the western flatlands and the eastern uplands. Infiltration potential remains moderate in these areas, as the slightly increased slope begins to promote some surface runoff. However, significant recharge still occurs, particularly where the gentle slopes coincide with permeable lithological units such as the Kanakavati sandstone.

- **Moderate (5–10°):** Found predominantly in the eastern part of the island, around the villages of Gadhada and Kalyanpar. At these slope angles, surface runoff begins to dominate over infiltration, reducing the proportion of rainfall that contributes to groundwater recharge. These areas act as transitional zones between recharge areas and runoff-generating uplands.
- **Moderately Steep (10–15°) and Steep (15–30°):** These slope classes are confined to the rocky outcrops of the eastern hills, where resistant Kanakavati sandstone and Jhurio shell-limestone form structural and denudational hills. These steep slopes generate high surface runoff during rainfall events and contribute negligible direct recharge. The exposed bedrock and thin soil cover further limit infiltration, making these areas sources of runoff that feed the ephemeral drainage network.

The slope analysis thus highlights a clear west-east dichotomy: the flat western region serves as the primary groundwater recharge zone, the gentle central slopes form a moderate infiltration transition zone, and the steep eastern hills function as runoff-generating areas with negligible recharge potential. This spatial pattern is consistent with the groundwater potential zoning presented in Chapter 5, where the "Good" zones are concentrated in the western low-slope areas and the "Poor" zones are confined to the eastern high-slope terrain.

4.4.1.3 Flow Accumulation

The flow accumulation map quantifies the spatial distribution of runoff concentration across the island. Flow accumulation values range from 0 to over 4,080 cells, representing the number of upstream cells that drain into each downstream cell. The map is classified into four categories based on the concentration of upstream flow as shown in figure 4.8:

- **Very Low (0–245 cells):** This class dominates the western part of the island. The very low flow accumulation indicates dispersed, diffuse flow with minor concentration. These areas correspond to the nearly level terrain where infiltration dominates over runoff, and surface water rarely concentrates into defined channels. The interpretation is one of dispersed low flow with minor surface concentration.
- **Low (246–585 cells):** This class represents small channels with low accumulation. These are typically first-order and second-order streams in the upper reaches of the drainage network, primarily in the central part of the island. Flow in these channels is intermittent and of low volume.
- **Moderate (586–1,900 cells):** This class indicates moderately high flow concentration and occurs in the middle reaches of the drainage network, where smaller tributaries

begin to coalesce into larger channels. These zones are transitional, with some potential for both runoff conveyance and infiltration, depending on local lithological and soil conditions.

- **High (1,900–4,080 cells):** This class represents major drainage channels with high flow concentration, confined primarily to the central and southern parts of the island. These high-accumulation zones are the primary conduits for monsoon runoff, representing major channels where flood concentration is highest. These zones are the most suitable locations for water harvesting structures such as check dams and percolation tanks.

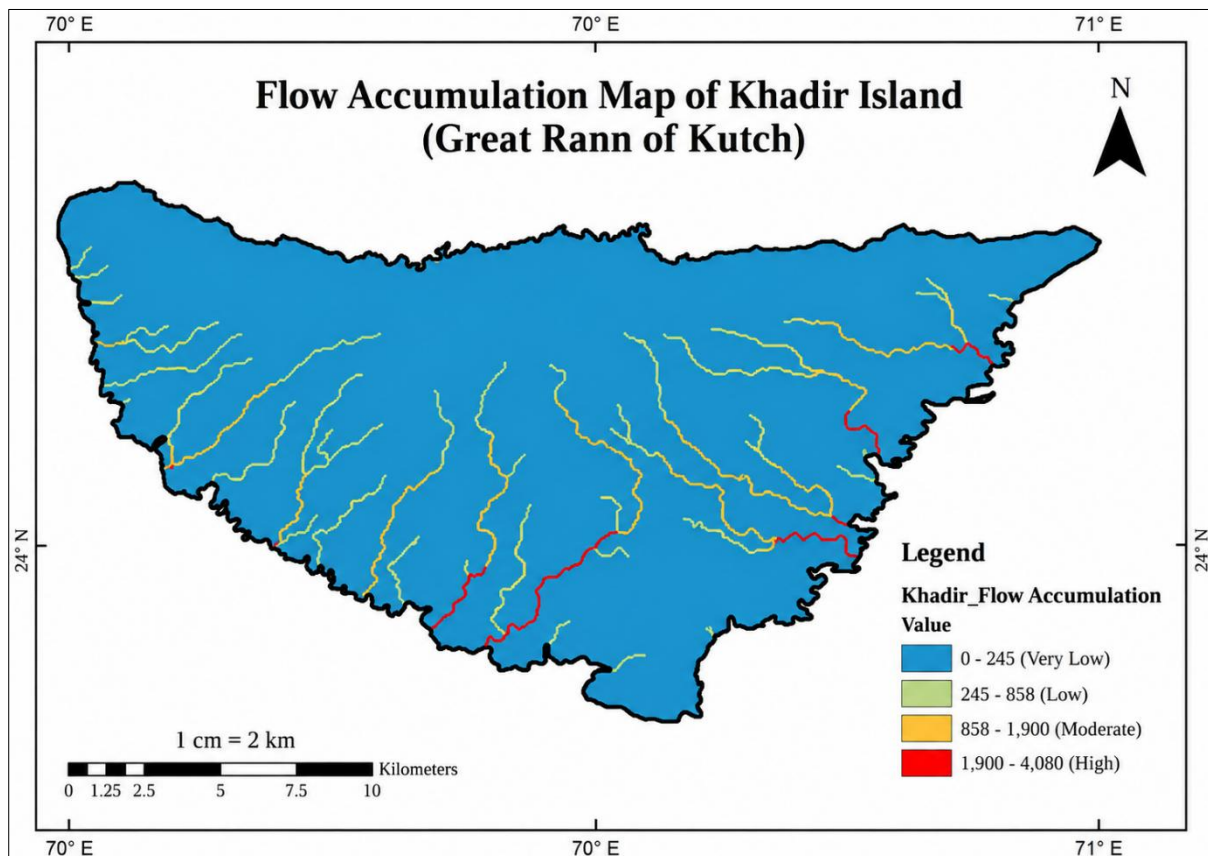


Figure 4.8: Flow Accumulation Map of Khadir Island (Source: Derived from SRTM DEM)

4.4.1.4 Hydrogeological Significance and Implications for Water Management

The integration of topographic, slope, drainage, and flow accumulation data provides critical insights for groundwater management on Khadir Island. The well-developed drainage network with low to moderate relief suggests favourable conditions for groundwater recharge in the western and central parts of the island. The low relief in these areas promotes infiltration and reduces surface runoff, allowing a greater proportion of monsoon rainfall to percolate into the subsurface. In contrast, the relatively steeper eastern terrain generates more runoff and less recharge, with discharge ultimately flowing towards the surrounding Rann.

The central-north ridge, with its higher elevation and steeper slopes, acts as a runoff-generating zone. The runoff from this elevated area flows radially outward through the dendritic drainage network, eventually concentrating in high-accumulation channels in the central and southern parts of the island. These high-flow zones represent the most promising sites for managed aquifer recharge (MAR) structures. Specifically, the high flow accumulation zones along the central-south drainage axes are prime sites for percolation tanks, check dams, and recharge shafts, as these structures can intercept and retain monsoon runoff, allowing it to infiltrate and replenish the underlying aquifer. The very low accumulation zones in the west, while not suitable for channel-based structures, have high infiltration potential and are ideal for distributed recharge interventions such as farm ponds and field bunding.

The topographic control on groundwater flow direction is equally significant. Groundwater flow generally follows the surface topography, moving from the higher central and eastern areas towards the lower western and southern margins. This flow pattern, confirmed by the hydraulic head contours generated from the MODFLOW model (Chapter 5), has important consequences for seawater intrusion. The seaward-directed hydraulic gradient that drives freshwater towards the coast is also the primary defence against the landward advance of the saline wedge. Any reduction in this gradient due to excessive pumping in the recharge zones weakens this defence and accelerates intrusion, as demonstrated in the seawater intrusion modelling presented in Chapter 5.

In summary, the topography and drainage analysis reveals that Khadir Island is a gently sloping landmass with a dendritic to sub-dendritic drainage network, a central-north topographic high, and a radial to centripetal flow direction. The western and central parts, characterised by flat terrain, low flow accumulation, low drainage density, and high infiltration potential, represent the island's primary natural recharge zones. The eastern part, with steeper slopes, higher drainage density, and higher flow accumulation, generates runoff that can be captured for managed recharge. The priority for water resource development should therefore be to site recharge structures in flat terrains with dense drainage convergence zones to maximise groundwater replenishment. This spatial understanding forms the foundation for the groundwater potential zoning, MAR site selection, and numerical flow modelling presented in the subsequent chapters.

4.4.2 Climatic Conditions:

Khadir Island falls within the arid tropical climatic zone according to the Köppen climatic classification (BWh). The climate is characterised by persistently high temperatures, low and erratic rainfall, high evaporation rates, and prolonged dry conditions throughout most

of the year. The arid nature of the climate plays a dominant role in controlling groundwater recharge, vegetation distribution, agricultural productivity, and overall water availability in the study area (IMD, 2022; Britannica, 1998).

The region experiences three major seasons:

1. Hot Dry Summer Season (March–June): This period is characterised by extremely high temperatures, intense solar radiation, strong dry winds, and negligible rainfall.
2. Southwest Monsoon Season (July–September): The majority of annual rainfall occurs during this short period. Temporary surface water accumulation and groundwater recharge take place during intense monsoon events.
3. Mild Dry Winter Season (October–February): Winter months are relatively cooler and more comfortable, although atmospheric humidity remains low and rainfall is generally absent.

The climatic conditions of Khadir Island are strongly influenced by its location within the Great Rann of Kachchh, which is surrounded by saline mudflats and seasonal marine inundation. The lack of dense vegetation cover and the highly reflective salt-encrusted surfaces further intensify the arid climatic conditions (Maurya et al., 2013).

4.4.2.1 Temperature

Temperature conditions in Khadir Island are extreme and exhibit large seasonal as well as diurnal variations. During the summer season (April to June), maximum temperatures frequently exceed 40°C and may reach up to 48–50°C during peak summer months, particularly in May. The combination of intense solar radiation, sparse vegetation, low humidity, and saline barren surfaces contributes to severe heat conditions across the island (IMD, 2022).

Night-time temperatures during summer generally remain between 25°C and 28°C, resulting in limited nocturnal cooling. Strong hot winds locally known as *loo* further aggravate the thermal stress conditions during daytime.

Winter months (December to January) are comparatively mild and pleasant during daytime, with average temperatures ranging from 25°C to 30°C. However, night-time temperatures decline significantly and may occasionally fall below 5°C. The minimum recorded temperature in the region is approximately 2°C. The winter season therefore exhibits a high diurnal temperature range, often exceeding 20°C, which is typical of arid continental environments (IMD, 2022; Britannica, 1998).

The large seasonal and diurnal temperature variations influence evapotranspiration rates, soil moisture retention, groundwater recharge, and agricultural practices within the study area.

4.4.2.2 Rainfall

Rainfall represents the most critical climatic parameter controlling groundwater recharge in Khadir Island. The region receives low, highly seasonal, and extremely variable rainfall both spatially and temporally. Based on long-term India Meteorological Department (IMD) records for the period 2001–2020, the mean annual rainfall of Khadir Island is approximately 419.8 mm (IMD, 2022).

Maps are presented using a common classification scheme to facilitate inter-annual comparison of rainfall variability. The rainfall map of the study area was prepared using IMD gridded rainfall datasets in the ArcGIS 10.8 environment. Since the geographical extent of Khadir Island is relatively small, covering approximately 315.2 km², the spatial variation in rainfall across the island is limited and the rainfall distribution is generally uniform throughout the study area.

However, slight spatial variation is observed across the island. The western part near Dholavira receives comparatively lower annual rainfall of approximately 380–400 mm, whereas the eastern part near Gadhada receives relatively higher rainfall ranging between 420 and 450 mm annually. Although this variation is not very significant because of the small areal extent of the island, it still influences local groundwater recharge conditions and groundwater potential distribution.

Rainfall in the region exhibits very high inter-annual variability, with a coefficient of variation of approximately 61%, indicating the uncertain and unpredictable nature of monsoonal rainfall. The wettest year during the study period was 2011, which received approximately 932 mm rainfall, while the driest year was 2018 with only about 103 mm rainfall (IMD, 2022). Such variability significantly affects groundwater recharge, agricultural productivity, and freshwater availability on the island.

The rainfall pattern is strongly seasonal. Nearly 89% of the annual rainfall occurs during the southwest monsoon period extending from June to September, with July generally being the wettest month. The remaining rainfall occurs sporadically during post-monsoon cyclonic events and occasional winter disturbances. Because most rainfall occurs within a short duration, groundwater recharge is concentrated mainly during intense monsoon events when infiltration temporarily exceeds runoff and evapotranspiration losses (Scanlon et al., 2006). Consequently, the capture and storage of monsoonal runoff through natural and artificial recharge mechanisms are essential for sustaining groundwater availability during the prolonged dry season and ensuring long-term water security on Khadir Island.

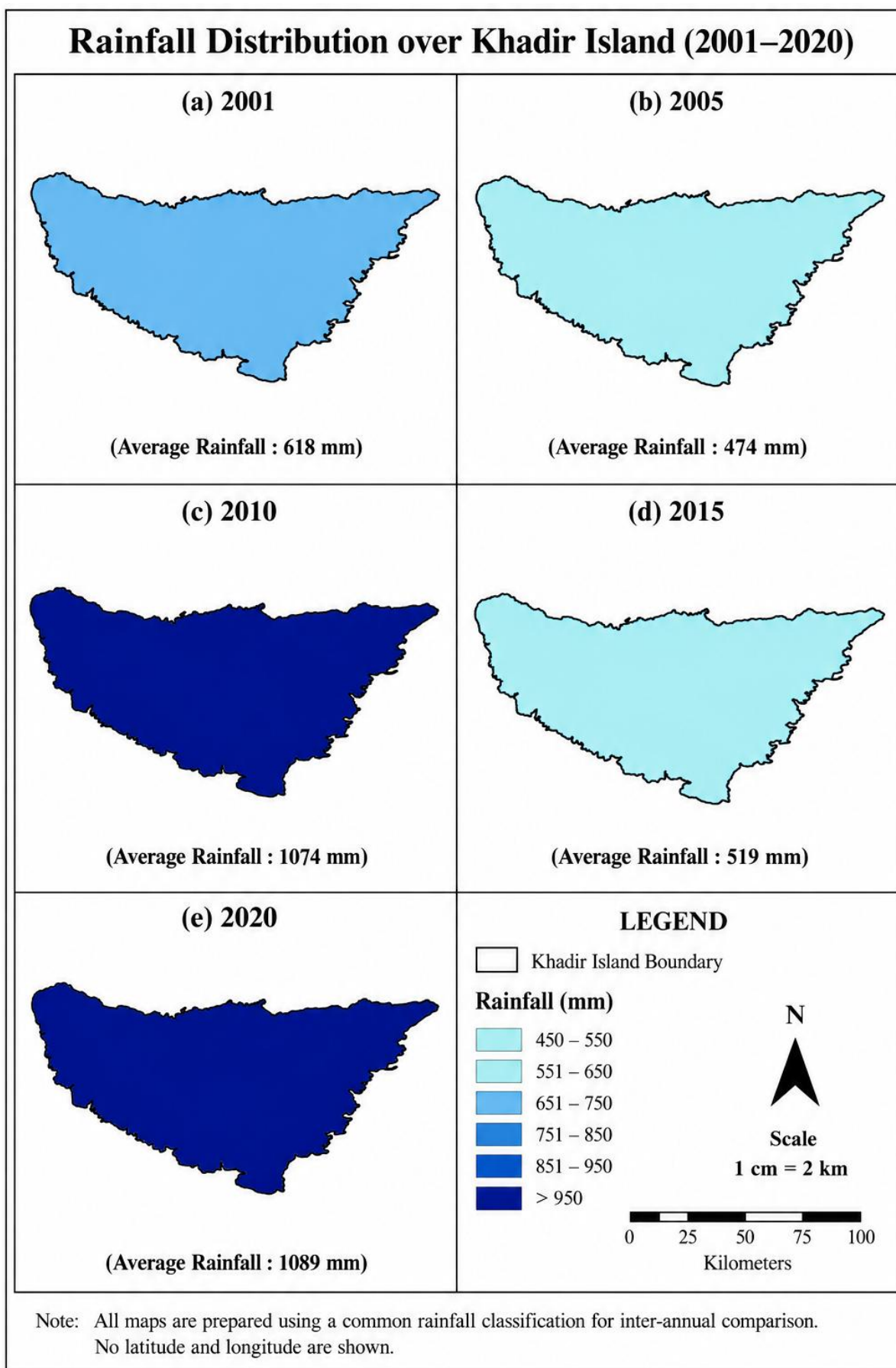


Figure 4.9: Spatial distribution of annual rainfall over Khadir Island for years (2001–2020).

4.4.2.3 Evapotranspiration

Evapotranspiration is one of the most important hydrological parameters controlling the regional water balance in arid environments. Due to high temperatures, low humidity, intense solar radiation, and persistent dry winds, evapotranspiration rates in Khadir Island remain extremely high throughout the year (Allen et al., 1998; IMD, 2022).

Potential Evapotranspiration (PET) data for the study area were obtained from authenticated meteorological datasets of the India Meteorological Department (IMD) and FAO-supported climatological databases based on the Penman–Monteith approach (Allen et al., 1998; IMD, 2022). The long-term mean annual PET for Khadir Island is approximately 2,140 mm/year, which is more than five times higher than the mean annual rainfall of the region.

The extremely high PET creates a permanent atmospheric water deficit condition across the island. Even during monsoon months, evapotranspiration demand remains sufficiently high to reduce effective infiltration and groundwater recharge. Recharge therefore occurs mainly during short-duration, high-intensity rainfall events when infiltration temporarily exceeds evaporative losses (Scanlon et al., 2006).

Actual Evapotranspiration (AET) is comparatively lower because soil moisture availability remains limited for most of the year. AET is estimated to range between 200 and 300 mm annually and primarily occurs during the monsoon and immediate post-monsoon period when surface moisture conditions temporarily improve (Healy and Cook, 2002). The large difference between annual rainfall and PET highlights the severe hydro-climatic stress conditions prevailing in Khadir Island and explains the fragile nature of groundwater recharge and freshwater sustainability in the region.

4.4.3 Geology and Lithology

Khadir Island forms part of the Kachchh sedimentary basin, a Mesozoic–Cenozoic rift basin that evolved as a consequence of the breakup of Gondwana and the subsequent tectonic evolution of the western Indian continental margin. The basin is structurally controlled by several major fault systems, including the Nagar Parker Fault to the north, the Kachchh Mainland Fault to the south, and the Katrol Hill Fault to the southeast (Biswas, 2005). These tectonic features have played a significant role in controlling sedimentation, basin subsidence, structural deformation, and groundwater occurrence within the region.

The Kachchh basin contains a thick sequence of sedimentary formations ranging in age from Triassic to Recent, with cumulative sediment thickness exceeding 3,000 m in the

basin depocentre. The stratigraphic succession includes sandstone, shale, limestone, marl, siltstone, alluvial deposits, and evaporitic sediments deposited under alternating marine, fluvial, deltaic, and continental environments (Biswas, 1992; Geological Survey of India, 2001; Biswas, 2016).

The geological evolution of the region has been strongly influenced by repeated phases of marine transgression and regression. During the Late Quaternary period, large parts of the present-day Great Rann of Kachchh were submerged under shallow marine conditions. Evidence of this marine transgression is preserved in the form of foraminifera, shell fragments, and other marine fossils observed within sediment cores and surface deposits (Maurya et al., 2013). The transgression, which initiated approximately 18,000 years before present, resulted in the deposition of fine-grained saline sediments across the Rann and adjacent island systems.

These marine-derived sediments now form the shallow subsurface lithology of Khadir Island and surrounding bays. As a consequence, the shallow aquifers are naturally saline to brackish in character. The inherited salinity from marine deposition, combined with present-day seawater intrusion and high evapotranspiration, exerts strong control on groundwater quality and freshwater availability within the study area.

4.4.3.1 Lithological Units of Khadir Island

The lithological framework of Khadir Island plays a fundamental role in controlling groundwater occurrence, recharge potential, permeability distribution, and groundwater quality. The lithological map of the study area was prepared using geological maps obtained from the Geological Survey of India (GSI) Bhukosh portal and further refined through remote sensing interpretation and field validation carried out during the field surveys of 2019 and 2021. Spatial analysis, digitization, and thematic map preparation were performed in the ArcGIS 10.8 environment. ([GSI Bhukosh Portal](#), [ISRO Bhuvan Portal](#))

Based on geological interpretation and field observations, five major lithological units were identified within Khadir Island. These units include Clayey Sand (Recent deposits), Khari Shale, Kanakavati Pink Sandstone, Jhurio Shell-Limestone, and Sandy Shale. The lithological distribution exhibits considerable spatial variation across the island and strongly influences hydrogeological conditions.

The western and central parts of Khadir Island are predominantly covered by recent clayey sand deposits. These deposits consist of fine- to medium-grained sand mixed with varying proportions of clay and silt. Due to their relatively loose texture, these sediments possess moderate to high infiltration capacity and support groundwater recharge during monsoon periods. However, because of their shallow occurrence and close association with

saline mudflats of the Rann, these deposits are highly susceptible to salinity ingress and evaporative salt accumulation.

Table 4.1: Lithological Units of Khadir Island

Lithological Unit	Area (km ²)	Percentage (%)	Hydrogeological Characteristics
Clayey Sand (Recent)	~168	~53.4	Moderate to high infiltration; vulnerable to salinity ingress
Shale (Khari)	~86	~27.3	Very low permeability; acts as aquitard
Pink Sandstone (Kanakavati)	~44	~13.9	Moderate to high permeability; principal aquifer
Shell-Limestone (Jhurio)	~14	~4.4	Secondary porosity through dissolution and fracturing
Sandy Shale	~3	~1.0	Intermediate hydraulic characteristics
Total	315	100	

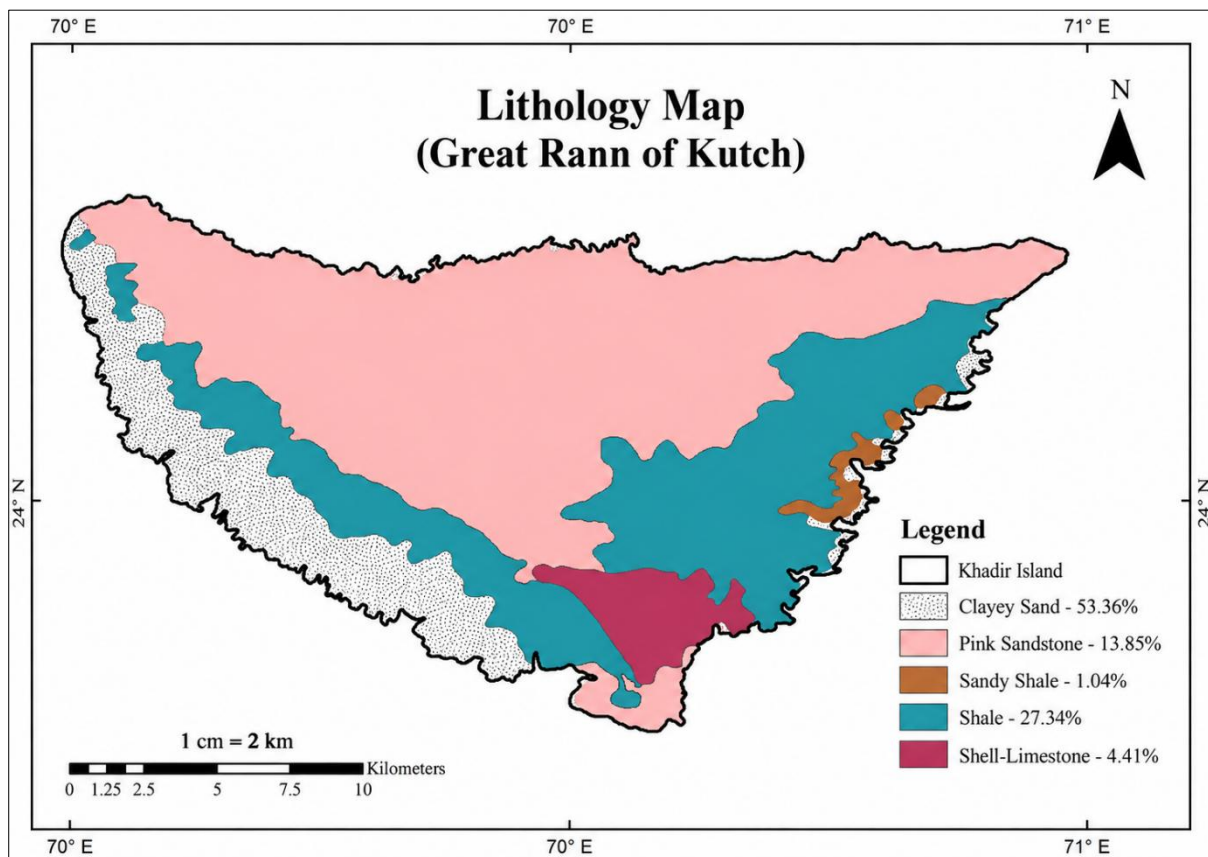


Figure 4.10: Lithological Map of Khadir Island

The Khari shale formation occupies a significant portion of the central and eastern sectors of the island. The shale is generally dark grey to black, fissile in nature, and contains clay minerals, pyrite, and organic matter. Owing to its compact and fine-grained characteristics, the permeability of this formation is extremely low. Consequently, the Khari shale acts as an aquitard restricting vertical groundwater movement and reducing recharge potential. Areas dominated by this formation generally exhibit poor groundwater quality and elevated salinity conditions.

The Kanakavati Pink Sandstone represents the principal aquifer unit of Khadir Island. This formation consists of fine- to medium-grained, moderately sorted sandstone with calcareous cementation. The sandstone exhibits favourable hydrogeological properties including moderate to high porosity and permeability. Available pumping test data and field observations indicate porosity values ranging between 15% and 25%, while hydraulic conductivity varies approximately between 0.5 and 2.8 m/day. The western region around Dholavira, Janan, and Ratanpar is largely associated with this sandstone formation and demonstrates comparatively better groundwater potential and lower salinity. Fractures and lineaments within the sandstone further enhance secondary permeability and groundwater movement.

The Jhurio Shell-Limestone formation occurs in limited patches mainly within the eastern part of the island. The formation is fossiliferous in nature and contains abundant shell fragments and calcareous material. Primary porosity within the limestone is relatively low; however, dissolution and fracturing processes create secondary porosity that enhances groundwater storage and transmissivity in localized areas.

Sandy shale forms a minor transitional lithological unit occurring between the shale and sandstone formations. The unit consists of sandy clay and shale mixtures exhibiting intermediate hydrogeological characteristics. Groundwater occurrence within this unit is generally discontinuous and controlled by local structural conditions and weathering patterns.

Overall, lithological variation exerts strong control on groundwater recharge, aquifer storage, permeability, and groundwater quality across Khadir Island. Sandstone-dominated western regions generally possess favourable hydrogeological conditions, whereas shale-dominated eastern regions are characterised by poor recharge potential and comparatively higher salinity. These lithological controls provide the basis for groundwater potential zoning and subsequent groundwater flow and seawater intrusion modelling carried out in the present study.

4.4.4 Geomorphology

Geomorphology plays an important role in controlling groundwater occurrence, infiltration, runoff behaviour, drainage characteristics, and groundwater recharge potential. The geomorphological characteristics of Khadir Island are primarily governed by tectonic activity, lithological variation, marine transgression, weathering, erosion, and depositional processes operating under arid climatic conditions.

The geomorphological map of Khadir Island was prepared using multi-season Landsat-8 and Sentinel-2 satellite imagery supported by SRTM DEM analysis, existing geomorphological information from the Geological Survey of India (GSI) Bhukosh portal, and detailed field validation conducted during 2019 and 2021. Spatial analysis, DEM interpretation, digitization, and thematic map preparation were carried out using ArcGIS 10.8 environment. ([GSI Bhukosh Portal](#), [ISRO Bhuvan Portal](#), [USGS Earth Explorer](#))

Based on satellite image interpretation and field observations, five major geomorphic units were identified on Khadir Island: Alluvial Plain, Denudational Hill, Pediplain, River/Water Bodies, and Structural Hill. These geomorphic units significantly influence groundwater recharge, aquifer storage, and groundwater movement across the island.

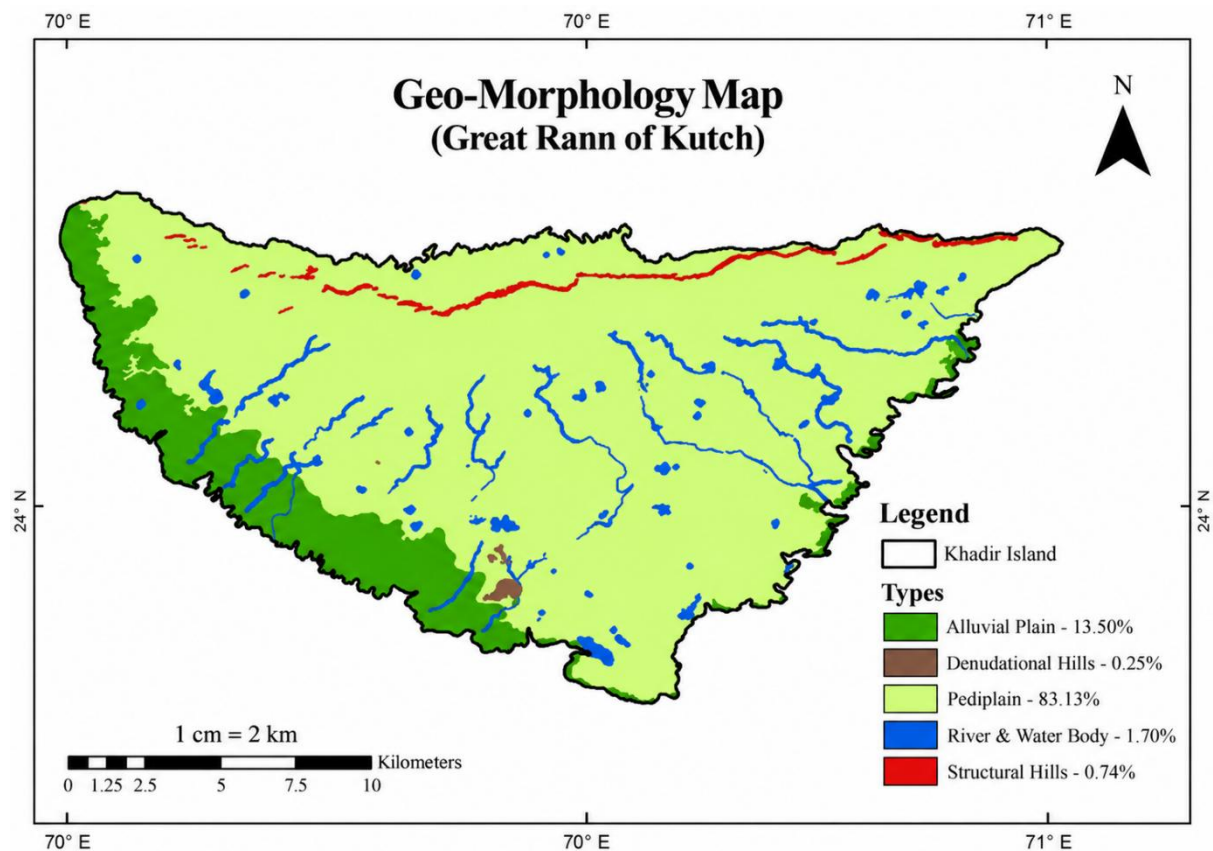


Figure 4.11: Geo-Morphological Map of Khadir Island

The pediplain unit is the most dominant geomorphic feature of Khadir Island, covering approximately 83.81% of the total geographical area. Pediplains are broad, gently sloping erosional surfaces developed under prolonged weathering and denudation processes in arid to semi-arid climatic conditions. These areas are generally covered by weathered materials and thin soil layers that permit moderate infiltration and groundwater recharge. Due to their extensive spatial distribution and favourable infiltration characteristics, pediplains represent the principal groundwater recharge zones of the island.

Alluvial plains occupy approximately 13.50% of the study area and are mainly distributed along drainage channels and low-lying regions. These plains consist of unconsolidated sediments such as sand, silt, clay, and gravel deposited by seasonal fluvial processes. Because of their comparatively high porosity and permeability, alluvial plains exhibit favourable groundwater occurrence and recharge conditions. Wells located within these zones generally show comparatively better groundwater potential and lower salinity.

Denudational hills occupy only 0.25% of the total area and are formed by long-term weathering and erosional processes acting on resistant rock formations. These areas are characterised by steep slopes, shallow weathered zones, and exposed bedrock surfaces. Consequently, infiltration is very low and surface runoff is high, resulting in poor groundwater potential.

Table 4.2: Areal Distribution and Hydrogeological Characteristics of Geomorphological Units on Khadir Island

Sr. No.	Geomorphic Unit	Area (km ²)	Percentage (%)	Hydrogeological Characteristics
1	Alluvial Plain	42.54	13.50	High infiltration and recharge potential; moderate to good groundwater occurrence
2	Denudational Hill	0.79	0.25	High runoff, low infiltration, poor groundwater potential
3	Pediplain	264.17	83.81	Moderate infiltration; major groundwater recharge zone
4	River / Water Bodies	5.36	1.70	Localized recharge through infiltration and surface storage
5	Structural Hill	2.34	0.74	Groundwater controlled by fractures and joints; limited recharge
	Total	315.20	100.00	

Structural hills constitute approximately 0.74% of the study area and are structurally controlled landforms associated with tectonic uplift, faults, joints, and resistant lithological formations. Groundwater occurrence within these units is generally limited and depends mainly on secondary porosity developed through fractures and joints. In fractured zones, localized groundwater movement and storage may occur; however, overall recharge potential remains low due to steep slopes and limited soil cover.

River channels and water bodies occupy approximately 1.70% of the study area and include seasonal streams, ponds, reservoirs, and check dams. Although limited in aerial extent, these geomorphic features play a significant role in localized groundwater recharge during monsoon periods. Surface water impoundment within these areas facilitates infiltration and temporary groundwater replenishment, especially where permeable alluvial materials are present.

Overall, the geomorphological setting of Khadir Island exerts strong control on groundwater occurrence and recharge distribution. Pediplains and alluvial plains generally exhibit favourable hydrogeological conditions, whereas denudational and structural hills are associated with poor groundwater potential and high runoff conditions. These geomorphic characteristics therefore form an important input parameter in groundwater potential zoning, managed aquifer recharge planning, and groundwater flow modelling carried out in the present study.

4.4.5 Lineament Density

Lineaments are linear or curvilinear features visible on the Earth's surface that represent subsurface geological structures such as faults, fractures, joints, shear zones, or lithological contacts. In hard rock and semi-consolidated sedimentary terrains, lineaments play a significant role in controlling groundwater occurrence, groundwater movement, and aquifer recharge because they act as preferential pathways for infiltration and subsurface flow (Sander, 2007; Magowe and Carr, 1999).

The lineament density map of Khadir Island was prepared using Landsat-8 Operational Land Imager (OLI) imagery with 30 m spatial resolution and Sentinel-2 Multispectral Instrument (MSI) imagery with 10 m spatial resolution. Satellite image interpretation was supported by hillshade analysis derived from SRTM DEM and validated through field observations conducted during the field surveys of 2019 and 2021. Thematic layer preparation, lineament extraction, density analysis, and spatial interpolation were carried out using ArcGIS 10.8 environment. (USGS Earth Explorer, Copernicus Open Access Hub)

The lineament density distribution of Khadir Island exhibits a distinct west-to-east variation. The western part of the island shows comparatively higher lineament density, whereas the eastern part is characterised by relatively sparse structural features. Most of the major lineament's trend in northeast–southwest and northwest–southeast directions, reflecting the regional tectonic framework of the Kachchh basin. The western region, including areas around Ratanpar and Janan, exhibits very high to high lineament density (>1.2 km/km²). These structurally controlled zones enhance secondary porosity and permeability within the sandstone formations, thereby facilitating groundwater recharge, groundwater storage, and groundwater movement. Field observations and well inventory data indicate comparatively better groundwater potential and lower salinity in these areas.

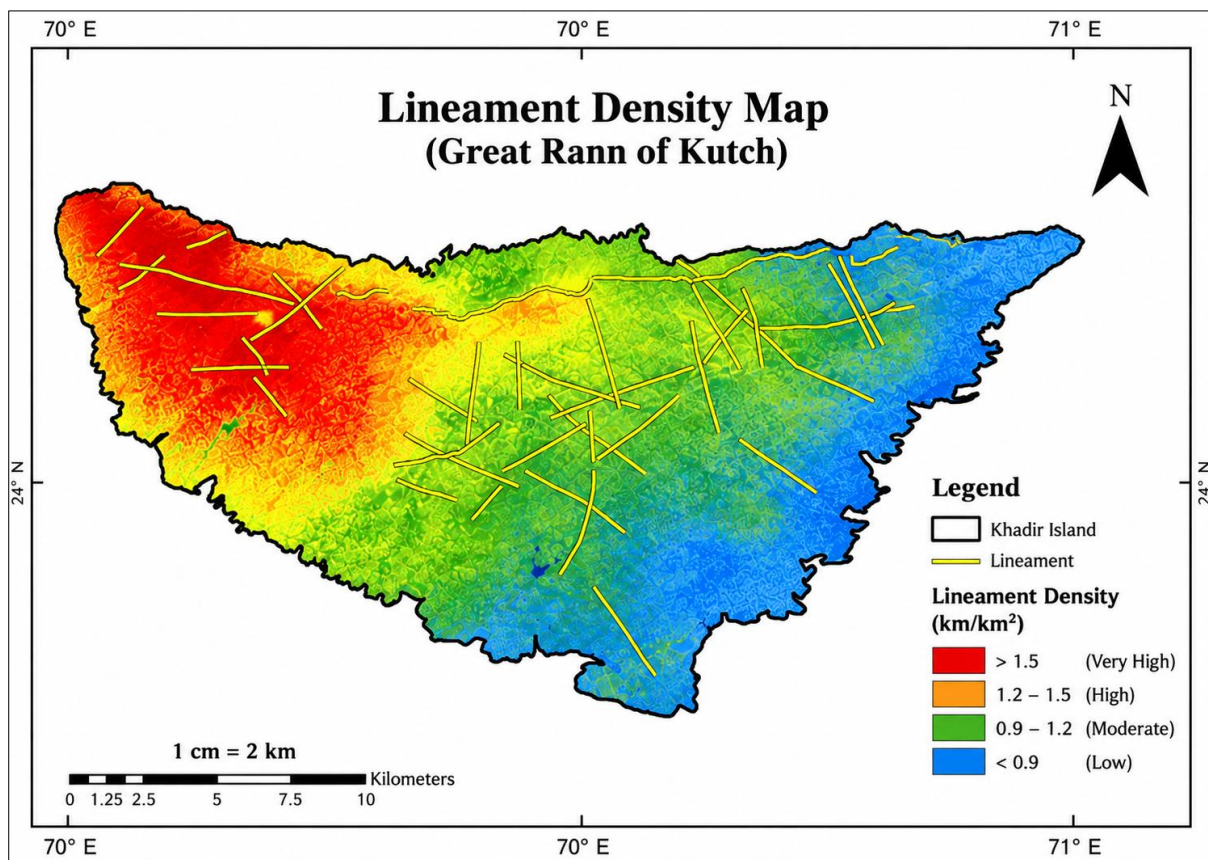


Figure 4.12: Lineament Density Map of Khadir Island (Source: Interpretation of Landsat-8 and Sentinel-2 imagery)

The west-central region near Dholavira shows moderate to high lineament density, which also supports favourable groundwater conditions. In contrast, the central and eastern parts of the island, including Kalyanpar and Gadhada, exhibit low lineament density (<0.9 km/km²). These regions are dominated by shale formations with limited fracturing and consequently show poor groundwater potential, lower well yields, and comparatively higher salinity conditions.

The hydrogeological significance of lineaments is particularly important in Khadir Island because groundwater occurrence within sandstone and semi-consolidated formations is largely controlled by secondary porosity developed through fractures and joints. Areas with high lineament density generally exhibit improved infiltration, higher transmissivity, and comparatively better groundwater quality. Conversely, areas with low lineament density are associated with poor recharge conditions and higher groundwater salinity.

Table 4.3: Lineament Density Classes and Hydrogeological Significance

Lineament Density Class (km/km ²)	Spatial Distribution	Representative Areas	Hydrogeological Characteristics
> 1.5 (Very High)	Western part	Ratanpar, Janan	High secondary permeability; enhanced recharge and groundwater movement
1.2 – 1.5 (High)	West-central part	Dholavira west	Moderate to high groundwater recharge through fractures
0.9 – 1.2 (Moderate)	Central part	Amrapar, Ganeshpar	Limited fracture-controlled recharge
< 0.9 (Low)	Eastern part	Kalyanpar, Gadhada	Low permeability and restricted groundwater movement

The lineament density map therefore forms an important thematic layer in groundwater potential zoning and was also used for identifying suitable locations for managed aquifer recharge structures such as recharge shafts, percolation tanks, and check dams in the present study.

4.4.6 Soil Characteristics of Khadir Island:

Soil characteristics play an important role in controlling infiltration, surface runoff, groundwater recharge, soil moisture retention, and groundwater quality. In arid and semi-arid regions such as Khadir Island, soil texture, permeability, salinity, and porosity significantly influence recharge conditions and groundwater potential distribution.

The soil map of Khadir Island was prepared using digitized FAO soil maps, satellite image interpretation, and field validation carried out during the field investigations of 2019 and

2021. Spatial analysis and thematic map preparation were performed in ArcGIS 10.8 environment. (FAO Soils Portal)

Based on soil texture, infiltration characteristics, salinity conditions, and geomorphological association, five major soil types were identified within the study area: Clayey Soils, Clay Loam Soils, Sandy Clay Loam, Coastal/Saline Clay, and Sandy Soils/Sand Dunes. These soil types exhibit considerable variation in infiltration capacity and hydrogeological behaviour across the island. Coastal or saline clay deposits occur along the margins of Khadir Island adjacent to the Great Rann of Kachchh. These soils are highly saline in nature and possess extremely low permeability. The presence of evaporitic salts and poor drainage conditions further limits infiltration and contributes to groundwater salinization in adjoining areas.

Sandy soils and localized sand dune deposits occur mainly near Ratanpar in the western part of the island. These soils possess high infiltration capacity because of their coarse texture and loose grain structure. Although their areal extent is limited, they represent localized zones of favourable groundwater recharge.

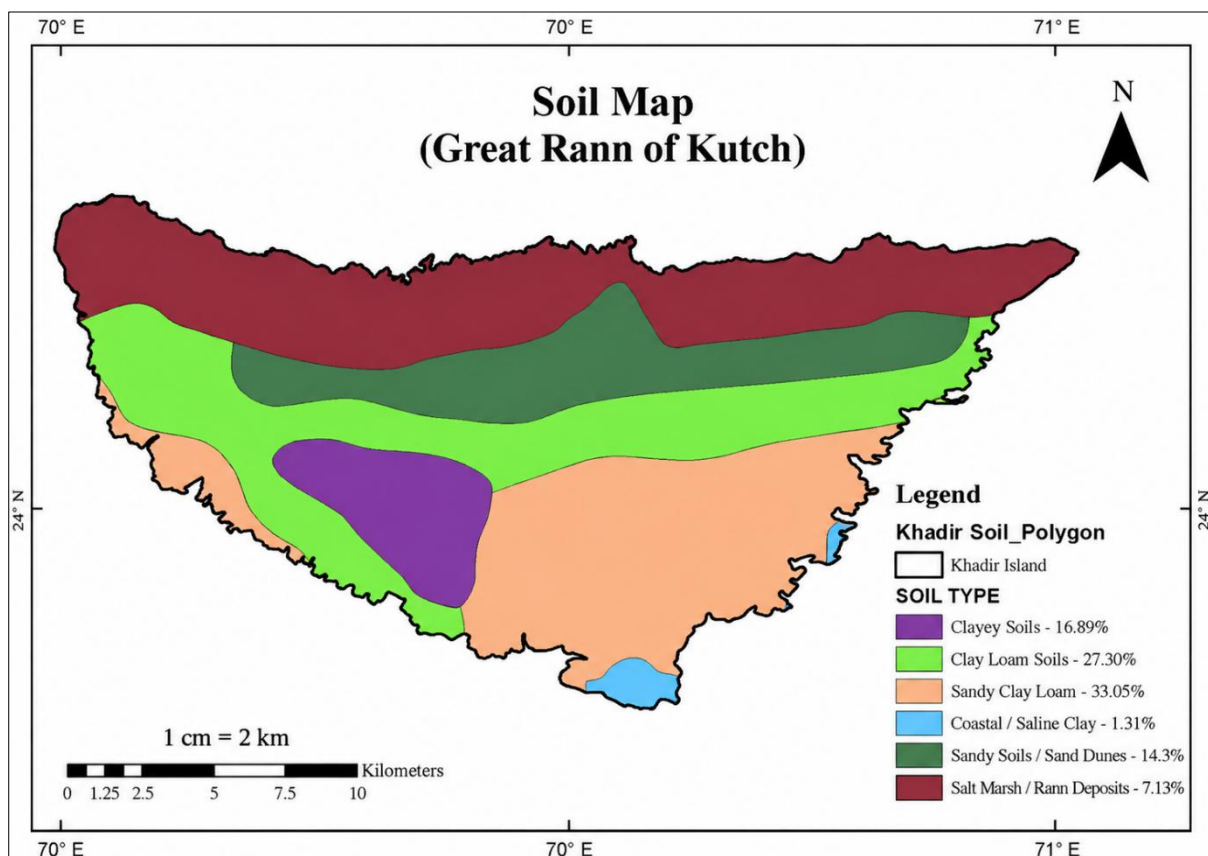


Figure 4.13: Soil Map of Khadir Island

Salt marsh and Rann deposits occur mainly along the northern fringe of the island and are associated with periodic saline inundation and evaporitic deposition. These areas

exhibit extremely poor infiltration conditions and negligible groundwater recharge potential due to high salinity and compact fine-grained sediments.

The dominant soil type of Khadir Island belongs primarily to Hydrological Soil Group C, which is characterised by slow infiltration when thoroughly wet. The effective porosity of the upper soil layer is estimated to be approximately 0.18, while the hydraulic conductivity is around 1.8 m/day. These characteristics indicate moderate recharge capability but also highlight the susceptibility of the shallow soil zone to salinity accumulation under high evapotranspiration conditions.

Overall, soil characteristics exert strong control on groundwater recharge and groundwater quality across Khadir Island. Western alluvial and sandy soil regions generally support comparatively better recharge conditions, whereas eastern clayey and saline soils are associated with poor infiltration and higher salinity risk. These soil characteristics therefore form an important thematic layer for groundwater potential zoning and managed aquifer recharge planning in the present study.

Table 4.4: Soil Types and Hydrogeological Characteristics of Khadir Island

Soil Type	Dominant Location	Infiltration Capacity	Area (%)	Hydrogeological Characteristics
Sandy Clay Loam	Western and central parts	Moderate	33.05	Moderate recharge potential; supports groundwater infiltration
Clay Loam	Central and eastern parts	Moderate to low	27.30	Reduced infiltration; moderate runoff generation
Clayey Soils	Small eastern patches	Very low	16.89	High runoff; poor recharge potential
Coastal / Saline Clay	Margins adjacent to Rann	Very low	1.31	High salinity; low permeability
Sandy Soils / Sand Dunes	Western patches near Ratanpar	High	14.30	High infiltration and localized recharge potential
Salt Marsh / Rann Deposits	Northern fringe	Very low	7.13	Saline conditions and negligible recharge

4.4.6 Land Use and Land Cover (LULC)

Land Use and Land Cover (LULC) mapping was carried out to understand the spatial distribution of land utilization patterns and their influence on groundwater recharge, infiltration characteristics, runoff generation, and hydrogeological conditions across Khadir Island. Multi-temporal LULC maps for the years 2001, 2010, and 2020 were prepared using Landsat and Sentinel-2 satellite imagery obtained from the United States Geological Survey (USGS) Earth Explorer and Copernicus Open Access Hub platforms. Additional reference datasets and validation support were obtained from the NRSC-Bhuvan thematic database (NRSC, 2020). Supervised classification techniques were applied in ArcGIS 10.8 followed by field verification and visual interpretation. [USGS Earth Explorer](#) Copernicus Open Access Hub [NRSC Bhuvan Portal](#).

The classified LULC maps for 2001, 2010, and 2020 are presented in Figures 4.19 to 4.20, while the statistical distribution of different land use classes is summarized in Table 4.5.

Table 4.5: Land Use / Land Cover Statistics of Khadir Island (2001–2020)

Sr. No.	LULC Class	2001 (%)	2010 (%)	2020 (%)	Trend
1	Water Bodies	0.67	0.28	0.12	Decreasing
2	Trees / Forest	0.01	0.03	0.07	Slight Increase
3	Agriculture	33.88	34.72	34.19	Stable
4	Built-up Area	0.83	0.86	1.11	Slow Increase
5	Bare Land	3.33	1.56	1.56	Decreasing
6	Rangeland	61.29	62.54	62.95	Stable / Slight Increase
	Total	100.00	100.00	100.00	

The most dominant LULC category throughout the study period is rangeland, covering approximately 61–63% of the total geographical area. The rangeland area increased slightly from 61.29% in 2001 to 62.95% in 2020. The predominance of rangeland reflects the traditional pastoral economy of Khadir Island, where livestock rearing remains the primary livelihood activity among Maldhari communities. These rangelands are mainly distributed across the northern and central parts of the island and provide moderate infiltration and recharge potential because of comparatively natural surface conditions (Government of Gujarat, 2020).

Agricultural land constitutes the second major land use category, occupying approximately 34% of the total area throughout the study period. Agricultural area increased marginally from 33.88% in 2001 to 34.72% in 2010, followed by a slight decline to 34.19% in 2020. Agricultural activities are concentrated mainly in the central and eastern villages such as Amrapar, Ganeshpar, Bambhanka, and Gadhada, where comparatively better soil conditions and groundwater availability support cultivation. The major crops include bajra, cumin, coriander, mustard, and seasonal vegetables. The relatively stable agricultural area indicates the limitations imposed by groundwater salinity, erratic rainfall, and restricted freshwater availability (IMD, 2022).

Built-up area, including settlements, roads, tourism infrastructure, and the Dholavira archaeological complex, increased gradually from 0.83% in 2001 to 1.11% in 2020. Although the areal extent remains limited, increasing built-up development may reduce groundwater recharge locally because impervious surfaces reduce infiltration capacity and increase surface runoff. Expansion of tourism infrastructure following the UNESCO World Heritage recognition of Dholavira in 2021 has further contributed to localized growth in built-up areas.

[UNESCO World Heritage Centre](#)

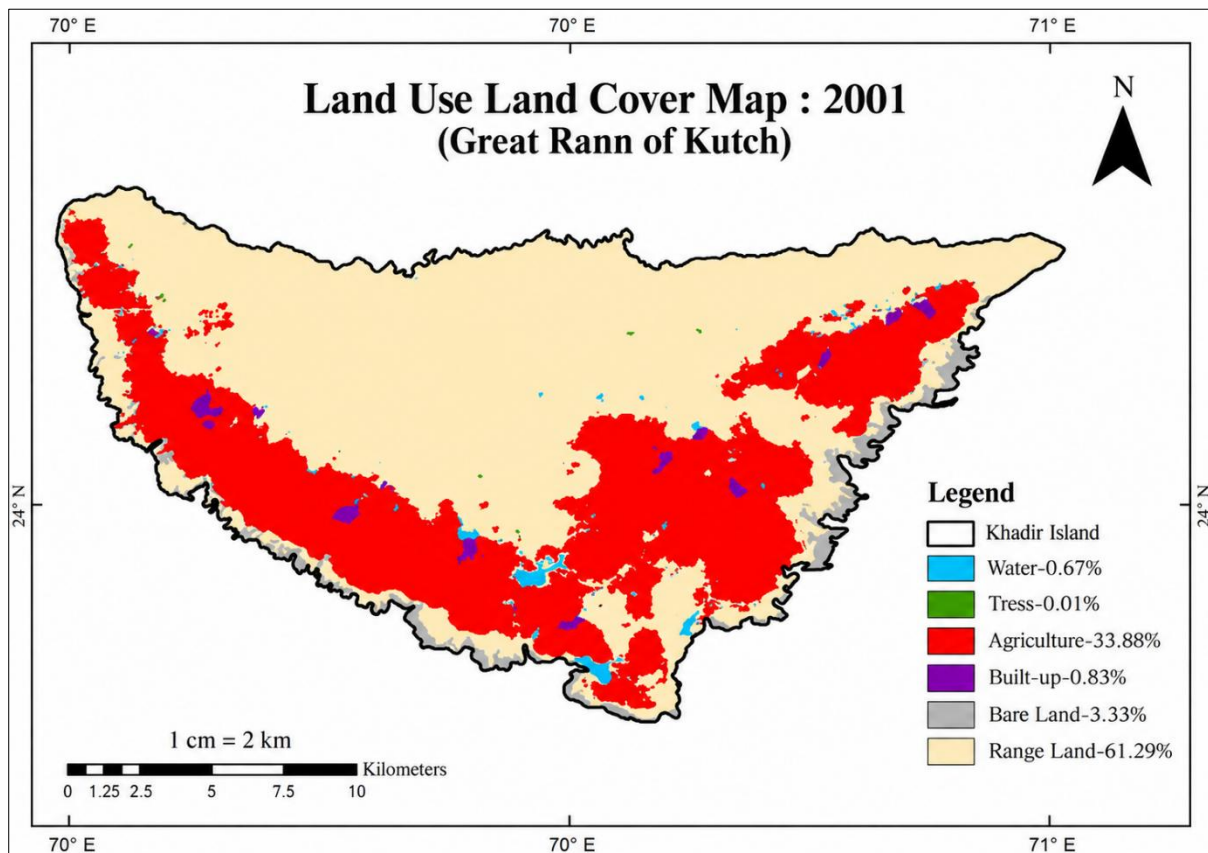


Figure 4.14: Land Use / Land Cover Map – 2001 (Source: Supervised classification of Sentinel-2 imagery)

Water bodies exhibit a continuous declining trend during the study period, decreasing from approximately 0.67% in 2001 to only 0.12% in 2020. This reduction may be attributed to variable monsoon rainfall, silting of traditional ponds and tanks, increased evaporation losses, and growing groundwater stress conditions. The reduction in surface water bodies is hydrogeologically significant because ponds, lakes, and seasonal water storage systems contribute to localized groundwater recharge and temporary freshwater storage within the arid environment of Khadir Island (Jha et al., 2007).

Bare land area declined from 3.33% in 2001 to 1.56% in both 2010 and 2020, indicating gradual conversion of barren surfaces into either agricultural land or rangeland. Tree and forest cover remains extremely limited because of the hyper-arid climate, saline soils, and low rainfall conditions. However, a minor increase from 0.01% in 2001 to 0.07% in 2020 was observed due to localized plantation activities and vegetation growth near settlements and recharge structures.

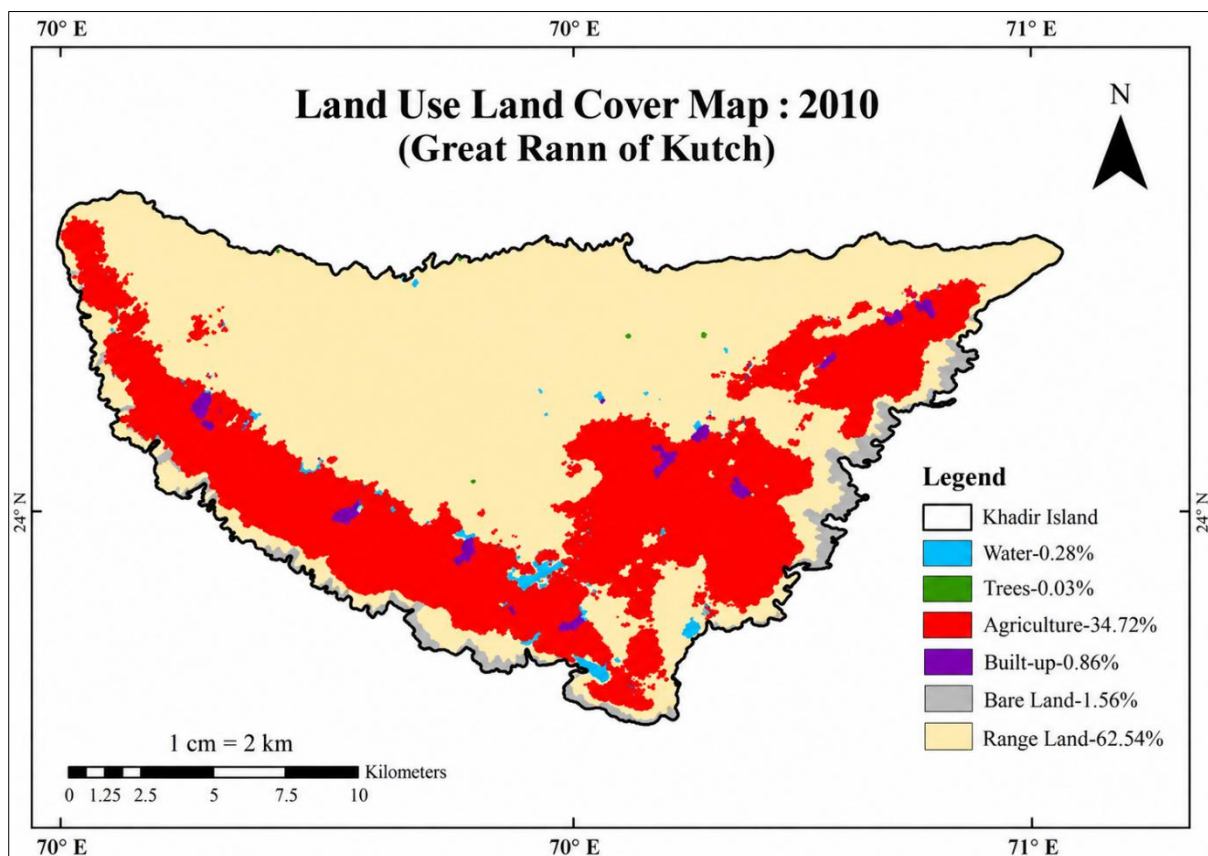


Figure 4.15: Land Use / Land Cover Map – 2010 (Source: Supervised classification of Sentinel-2 imagery)

The LULC pattern strongly influences groundwater recharge and hydrogeological behaviour across Khadir Island. Rangelands and alluvial plains exhibit comparatively favourable infiltration and recharge conditions because of lower runoff generation and

permeable surface materials. Agricultural areas provide moderate recharge depending upon soil texture, irrigation practices, and cropping patterns. In contrast, built-up areas and barren rocky surfaces generate higher runoff and lower infiltration. Surface water bodies directly support localized recharge and temporary freshwater storage systems.

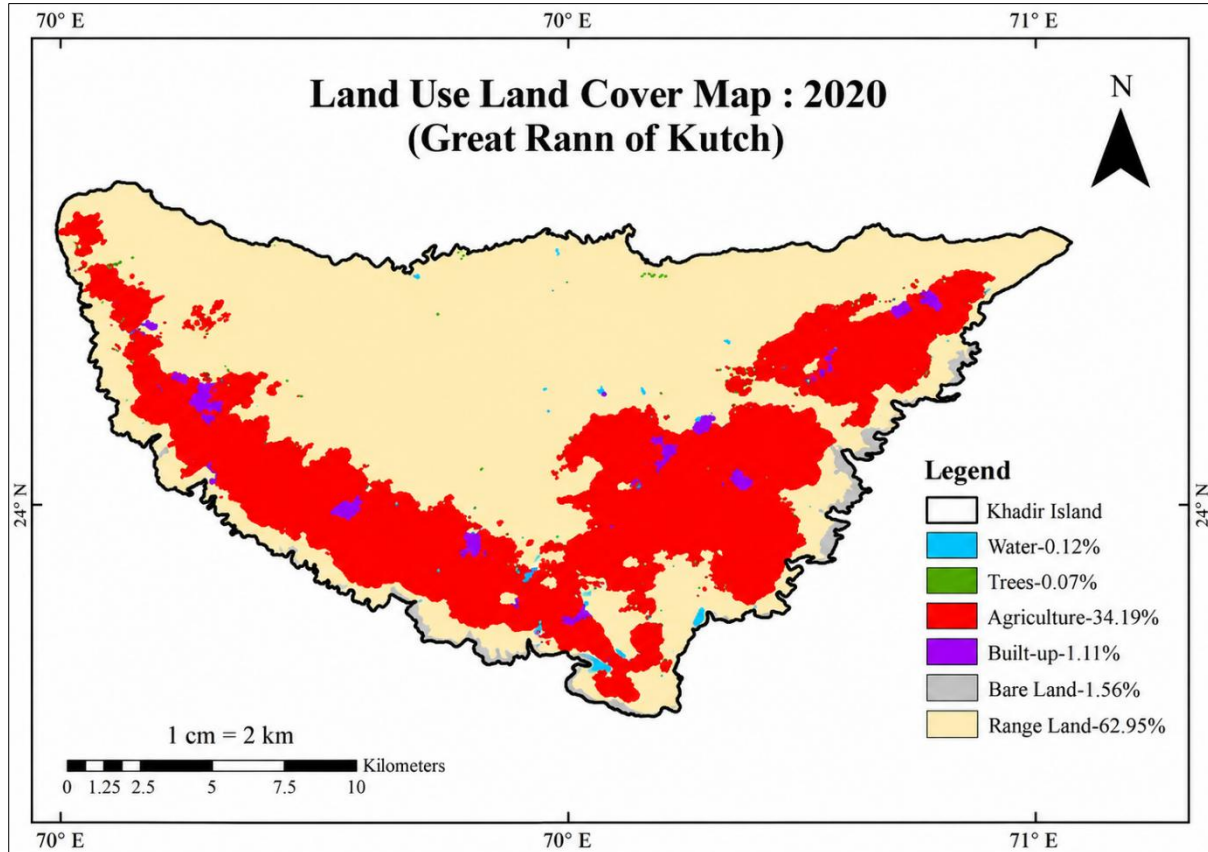


Figure 4.16: Land Use / Land Cover Map – 2020 (Source: Supervised classification of Sentinel-2 imagery)

The temporal analysis indicates that although major land use categories remained relatively stable between 2001 and 2020, declining water bodies and increasing built-up areas may adversely affect future groundwater recharge conditions. Therefore, sustainable land use planning, conservation of rangelands, restoration of traditional ponds, and protection of recharge zones are essential for maintaining groundwater sustainability and ecological balance within Khadir Island (Sander, 2007; NRSC, 2020).

PART B: FIELD INVESTIGATIONS

4.5 Field Investigations: Introduction

Field investigation forms the foundation of any hydrogeological study by providing ground-truth information required for validating remote sensing interpretation, hydrogeological analysis, numerical modelling, and conceptual understanding of aquifer systems (Todd and Mays, 2005; Fetter, 2018). Although satellite-based techniques are effective for identifying geomorphic features, drainage patterns, lithological boundaries, and structural elements, direct field observations are essential for understanding groundwater occurrence, aquifer behaviour, groundwater quality, and subsurface hydrogeological conditions.

The field investigations carried out during the present study played an important role in validating thematic layers prepared through RS-GIS analysis and in developing the conceptual hydrogeological framework of Khadir Island. Field-based observations were also used to verify lithological units, groundwater potential conditions, lineament-controlled groundwater occurrence, salinity distribution, and recharge characteristics across different parts of the island (Sander, 2007; Jha et al., 2007).

Two systematic field campaigns were conducted on Khadir Island during the post-monsoon periods of 2019 and 2021. The post-monsoon season was specifically selected because groundwater levels remain relatively high immediately after monsoon recharge and groundwater quality conditions are comparatively less concentrated due to dilution effects. This period therefore provides favourable conditions for assessing aquifer recharge response, groundwater occurrence, and hydrochemical characteristics (Freeze and Cherry, 1979).

A total of eight representative wells (KW-01 to KW-08) were inventoried across major villages and hydrogeologically significant locations including Ratanpar, Janan, Dholavira, Kalyanpar, areas near check dams, and a natural spring zone. The wells were selected to represent different lithological formations, geomorphic settings, groundwater quality conditions, and groundwater abstraction patterns across the island.

During the field investigations, detailed observations were recorded regarding:

- Well depth and construction,
- Groundwater level conditions,
- Groundwater salinity and water quality,

- Lithological exposures,
- Structural features such as fractures and joints,
- Recharge structures,
- Drainage conditions,
- Land use and cropping patterns,
- Water supply infrastructure.

GPS coordinates of observation wells and important hydrogeological features were also recorded for integration within the GIS database. Field photographs and site documentation were used to support subsequent hydrogeological interpretation and validation of thematic layers prepared in ArcGIS 10.8 (Jha et al., 2007).

The information obtained through field investigations provided critical input for groundwater potential zoning, groundwater flow modelling, seawater intrusion assessment, and preparation of the integrated water resource development plan presented in subsequent chapters of the thesis (Anderson et al., 2015).

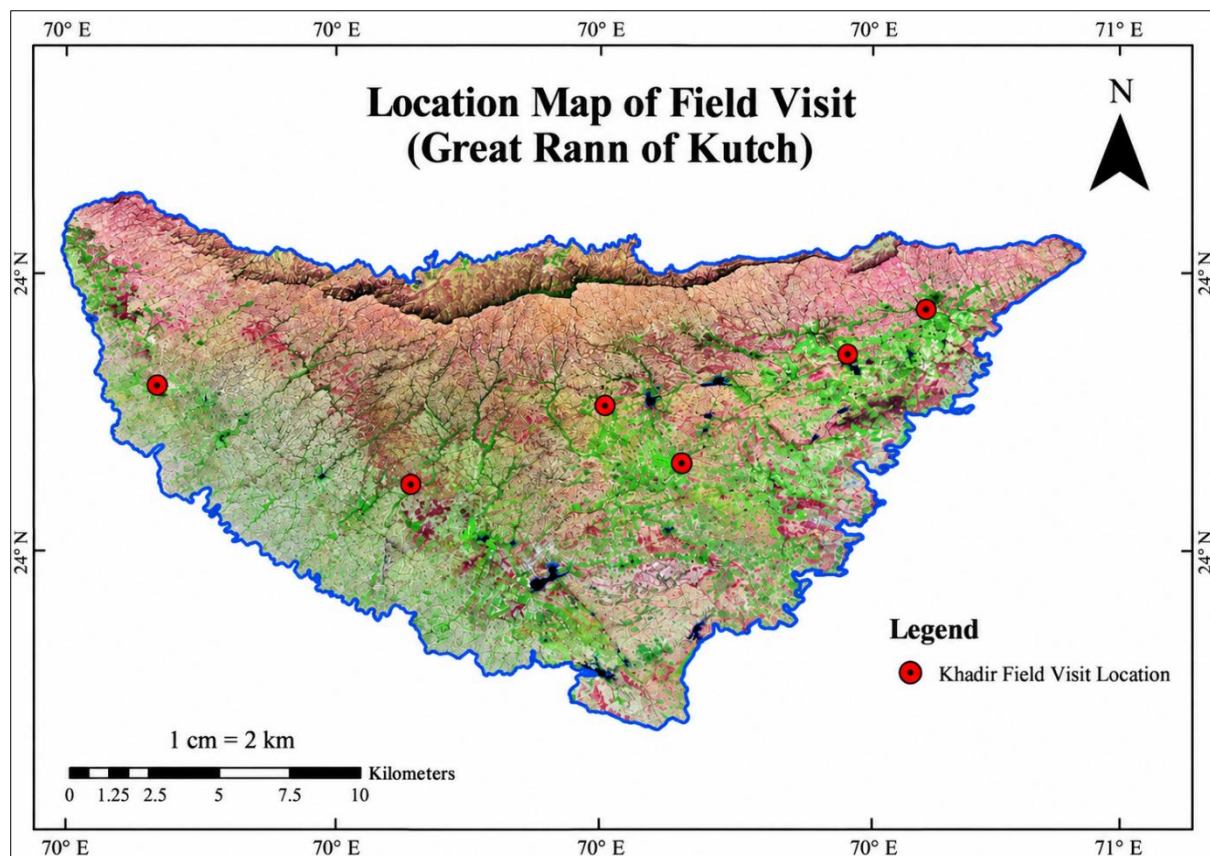


Figure 4.17: Location Map of Well Inventory

4.6 Field Investigations: Well Inventory

The first task during each field visit was to locate and document wells that could serve as validation points for the groundwater potential zone map and as reference points for

the numerical models. A total of eight wells were inventoried, covering the major villages and geomorphic units of Khadir Island. These wells are designated as KW-01 through KW-08.

For each well, the following information was recorded where available: type (government or private), village, UTM coordinates (using a handheld GPS with ± 3 m accuracy), pH, total dissolved solids (TDS), temperature, well depth, motor depth, lithological observations, structural features, and cropping pattern in the vicinity.

Table 4.6: Well Inventory from Field Surveys (Post-Monsoon 2019 and 2021)

Well ID	Type	Village	UTM Easting (m)	UTM Northing (m)
KW-01	Private	Ratanpar	622555	2641786
KW-02	Govt.	Janan	630527	2638524
KW-03	Govt.	Janan	636778	2641319
KW-04	Private	Dholavira	636778	2641319
KW-05	Govt.	Dholavira	639108	2639432
KW-06	Natural Spring	—	644312	2643120
KW-07	Govt.	Near Check Dam	646653	2644599
KW-08	Private	Near Check Dam	646653	2644599

4.7 Field Investigations: Water Quality Measurements

The groundwater quality analysis reveals pronounced spatial variability across Khadir Island, primarily controlled by lithology, recharge conditions, and structural influences.

The lowest TDS values (250–260 mg/L) were recorded at KW-04, located downstream of a reservoir, indicating active recharge and dilution of groundwater through surface water storage structures and permeable sandstone formations. In contrast, the highest TDS values (4,850–4,900 mg/L) were observed at KW-06, a natural spring, suggesting the discharge of deeper, saline groundwater likely influenced by structurally controlled pathways such as fractures or bedding planes.

Wells located in Janan village (KW-02 and KW-03) exhibited comparatively better groundwater quality, with TDS values ranging from 1,180 to 1,550 mg/L. This is attributed to the presence of highly weathered sandstone, which enhances secondary porosity and facilitates effective recharge.

A comparison between the 2019 and 2021 datasets indicates a slight reduction in TDS across most wells, reflecting improved recharge conditions during intervening monsoon

periods or reduced groundwater abstraction. However, the overall spatial distribution pattern of groundwater salinity remained consistent, suggesting that lithological and structural controls continue to dominate groundwater quality variations in the region.

Table 4.7: Groundwater Quality and Field Measurements

Well ID	Year	pH	TDS (mg/L)	Temp (°C)	Depth (ft)	Motor Depth (ft)
KW-01	2019	7.0	258	28.5	250	200
KW-01	2021	7.1	245	28.0	250	200
KW-02	2019	7.0	1550	31.5	600	350
KW-02	2021	7.0	1480	30.5	600	350
KW-03	2019	6.9	1200	25.0	420	360
KW-03	2021	6.8	1180	25.0	420	360
KW-04	2019	7.0	260	25.3	60	50
KW-04	2021	6.8	250	25.5	60	50
KW-05	2019	7.5	1800	25.3	250	200
KW-05	2021	7.4	1750	25.0	250	200
KW-06	2019	7.5	4900	24.5	—	—
KW-06	2021	7.5	4850	24.5	—	—
KW-07	2019	7.0	2700	24.5	300	250
KW-07	2021	7.1	2650	24.5	300	250
KW-08	2019	7.0	1975	24.5	300	250
KW-08	2021	7.0	1900	24.5	300	250

4.8 Field Investigations: Lithological and Structural Observations

The lithological and structural observations reveal that groundwater occurrence and quality in Khadir Island are strongly controlled by geological formations and structural features.

Key observations:

- Sandstone formations, particularly when highly weathered, act as productive aquifers due to enhanced secondary porosity and permeability.
- Shale intercalations act as semi-confining layers, leading to the development of deeper confined aquifers with comparatively better water quality.
- Igneous rock encountered at depth (450 ft in Janan) acts as a basement, influencing aquifer thickness and flow dynamics.

- Fossiliferous limestone indicates marine depositional environments and contributes to localised variations in permeability.
- Fault planes (KW-01) significantly influence groundwater movement, acting as either conduits or barriers, and explaining localised variations in TDS.

The observed variation in groundwater quality across wells is therefore a combined function of lithology, structural control, and recharge conditions.

Table 4.8: Lithological and Structural Observations from Field Visits

Well ID	Lithology and Key Observations	Cropping Pattern	Remarks
KW-01	Fault planes observed; nearby borewell shows lower TDS	Bajra, Jeera, Fruits, Vegetables	Two fault planes nearby
KW-02	Igneous rock at 450 ft; coarse sandstone; artesian well inactive	Bajra, Jeera, Fruits, Vegetables	Good water quality
KW-03	Highly weathered sandstone; continuous pumping	Bajra, Jeera, Fruits, Vegetables	Highly weathered pink sandstone
KW-04	Coarse sandstone; located near reservoir	Bajra, Jeera, Fruits, Vegetables	Lowest TDS; downstream of dam
KW-05	Brackish water up to 200 ft; multiple borewells	Bajra, Jeera, Fruits, Vegetables	Water brackish up to 200 ft
KW-06	Sandstone with shale intercalation; high TDS	—	Natural spring; highest TDS
KW-07	Fossiliferous limestone formation	Bajra, Jeera, Fruits, Vegetables	Fossiliferous limestone in upper part
KW-08	Sandstone with shale; good quality water below 200 ft	Bajra, Jeera, Fruits, Vegetables	Good quality below 200 ft

4.9 Field Investigations: Cropping Pattern Documentation

During the field visits, the crops being cultivated in the vicinity of each well were recorded through direct observation and informal interviews with farmers. This information is essential for understanding irrigation water demand, which is a major component of the overall water budget.

The dominant cropping pattern observed across all agricultural wells was bajra (pearl millet), jeera (cumin), fruits, and vegetables. Bajra is a hardy, drought-tolerant cereal that is well adapted to the arid climate and saline soils of Khadir Island. Jeera (cumin) is a high-value

cash crop that requires careful water management. Fruits and vegetables are grown where irrigation water is available, mostly from wells or from storage in the Dholavira reservoirs and check dams.

No significant variation in cropping pattern was observed between villages or between the two visits. Farmers in Ratanpar, Janan, Dholavira, and the areas near check dams all reported similar crop choices. This uniformity simplifies the water demand assessment, as a single set of crop water requirements can be applied across the agricultural areas.

4.10 Field Investigations: Government Monitoring Well Data

In addition to the eight wells inventoried during field visits, long-term monitoring data were obtained from two wells maintained by the Central Ground Water Board (CGWB) and the Gujarat Water Resources Development Corporation (GWRDC). These wells—KC-13 at Dholavira and HPII_KCH_006 at Kalyanpar—are not part of the field inventory (Table 3.5) but are essential for validating the seawater intrusion model presented in Chapter 5.

Table 4.9: Government Monitoring Well Data — 5-Year Averages

Year	Well	Avg Water Level (m bgl)	Avg TDS (mg/L)	Avg Cl ⁻ (mg/L)	Status
1995	KC-13 (Dholavira)	5.95	1220	120	Good water level and quality
2000	KC-13 (Dholavira)	8.05	—	—	Water level declined
2005	KC-13 (Dholavira)	7.93	4555	2340	TDS increased sharply
2010	KC-13 (Dholavira)	7.80	8875	4760	Very high salinity
2015	KC-13 (Dholavira)	Dry	Dry	Dry	Well completely dry
2020	KC-13 (Dholavira)	10.20	2720	1000	Recovered; TDS improved
2015	HPII_KCH_006 (Kalyanpar)	7.65	7170	4140	High salinity
2020	HPII_KCH_006 (Kalyanpar)	7.28	7250	4300	Persistent high salinity

Note: — indicates data not available.

Table 4.10: Key Observations — Trend Comparison Between Wells

Parameter	KC-13 (Dholavira) Trend	HPII_KCH_006 (Kalyanpar) Trend
Water Level	Declined from 5.95 m to 10.20 m; went dry in 2015	Relatively stable (~7.3–7.7 m bgl)
TDS	Increased from 1,220 to 8,875 mg/L; recovered to 2,720 mg/L	High and stable (~7,200 mg/L)
Chloride (Cl ⁻)	Increased from 120 to 4,760 mg/L; dropped to 1,000 mg/L	High and stable (~4,200 mg/L)
Seasonal Variation	Post-monsoon recovery visible	Extreme variation observed

4.10.1 Key Insight of the Long-term Monitoring Well:

The long-term groundwater records indicate significant spatial variation in groundwater behaviour between the western and eastern parts of Khadir Island. The Dholavira monitoring well (KC-13), situated within the western sandstone-dominated region, initially exhibited comparatively good groundwater quality with lower salinity conditions during the early monitoring period. However, progressive groundwater extraction and declining recharge conditions resulted in gradual deterioration of groundwater quality, increased TDS concentration, and temporary drying of the well around 2015. Subsequent partial recovery observed after 2020 indicates that the western region still retains moderate groundwater recovery potential under favourable recharge and controlled abstraction conditions.

In contrast, the Kalyanpar monitoring well (HPII_KCH_006), located within the eastern sector of the island, consistently exhibits high salinity and poor groundwater quality. Hydrochemical indicators, particularly elevated TDS and chloride concentrations along with low Na⁺/Cl⁻ ratios, suggest persistent seawater intrusion within the eastern aquifer system. Unlike Dholavira, the Kalyanpar region shows limited natural recovery potential due to unfavourable lithological conditions, low lineament density, poor recharge characteristics, and continued salinity ingress from the surrounding Rann environment.

The comparative hydrogeological analysis demonstrates that lithology alone does not govern groundwater quality and groundwater sustainability within Khadir Island. Structural controls such as faults, fractures, and lineaments significantly influence groundwater movement and recharge conditions by enhancing secondary permeability within sandstone

formations (Sander, 2007). Similarly, geomorphological and terrain-related factors including proximity to alluvial plains, slope conditions, drainage density, and infiltration characteristics strongly affect recharge potential and groundwater quality distribution across the island.

The western part of Khadir Island, particularly around Dholavira, exhibits comparatively favourable hydrogeological conditions due to moderate recharge potential, higher lineament density, lower drainage density, and the presence of permeable sandstone formations. These conditions provide opportunities for groundwater recovery through managed aquifer recharge and sustainable groundwater management practices. Conversely, the eastern region around Kalyanpar is characterised by poor recharge conditions, shale-dominated lithology, low structural permeability, and persistent seawater intrusion, resulting in a permanent intrusion zone with limited recovery potential. Consequently, the eastern region requires alternative water supply strategies, strict groundwater abstraction control, and artificial recharge interventions for long-term water security.

4.11 Existing Water Infrastructure of Khadir Island

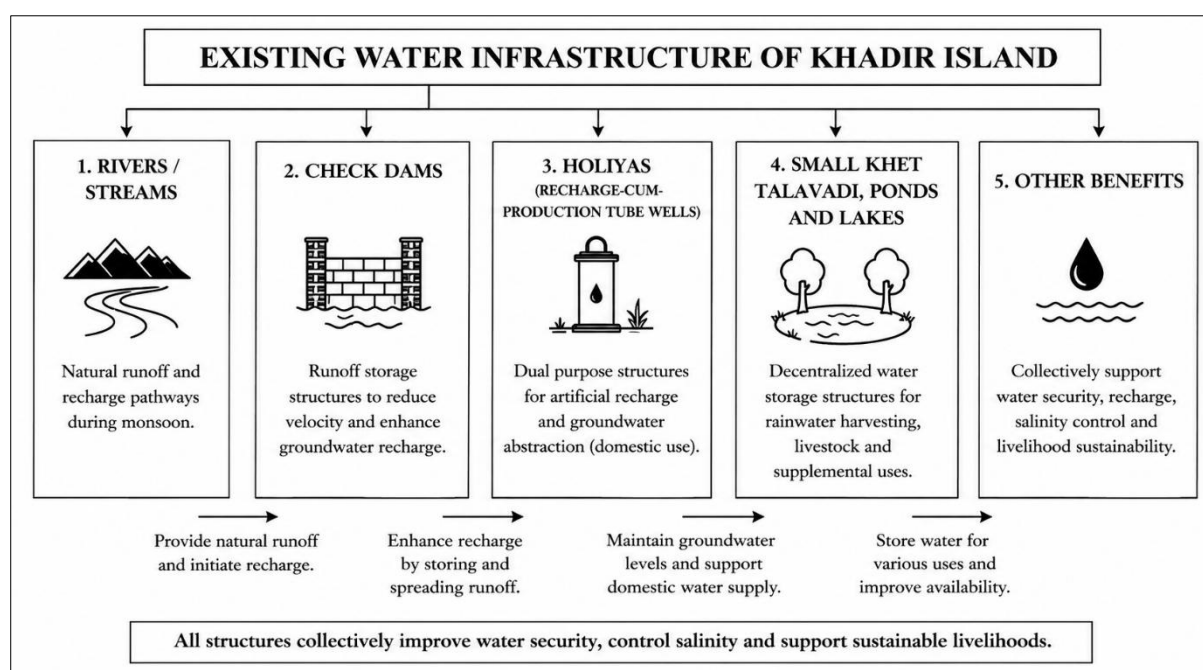


Figure 4.18: Existing Water Infrastructure of Khadir Island

The existing water infrastructure of Khadir Island reflects a combination of traditional water harvesting systems, natural drainage networks, modern groundwater recharge interventions, and decentralized village-level storage structures developed to cope with the arid and saline environment of the Great Rann of Kachchh. Due to low rainfall, high evapotranspiration, and limited freshwater availability, these water infrastructures play a

critical role in supporting domestic water supply, groundwater recharge, livestock requirements, and local livelihood sustainability.

4.11.1 Rivers and Seasonal Streams:

The island contains several seasonal drainage channels and river systems that function as important natural recharge pathways during the monsoon period. Among these, the Manhar River located east of Dholavira and the Mansar River located west of Dholavira are historically significant drainage systems associated with the ancient Harappan settlement of Dholavira. Archaeological evidence suggests that the Harappan civilization developed sophisticated rainwater harvesting and reservoir systems utilizing runoff from these seasonal streams (Archaeological Survey of India, 2015).

Other seasonal streams such as Pir Vokla near Ganeshpar and Vadiyavalo Vokla near Amrapar continue to contribute to local runoff conveyance and groundwater recharge during monsoon periods. Although these streams remain dry for most of the year, they serve as important hydrological conduits during intense rainfall events.

4.11.2 Check Dams:

Check dams represent one of the most important groundwater recharge interventions on Khadir Island. Structures such as Check Dam No. 224 near Ganeshpar and Check Dam No. 278 near Amrapar were constructed around 2001 under state-level water resource development initiatives by the Irrigation Engineering Department (IED), Government of Gujarat.

These check dams are designed to temporarily impound monsoon runoff, reduce flow velocity, enhance infiltration, and promote groundwater recharge within nearby aquifers. Field observations indicate that groundwater levels in areas surrounding check dams generally exhibit comparatively better recharge conditions and reduced salinity during post-monsoon periods. Check dams therefore play an important role in mitigating groundwater depletion and improving local water security.

4.11.3 Holiyas (Recharge-cum-Production Tube Wells):

Under the Sardar Patel Participatory Jal Sanchay Yojana (SPSJSY), approximately 30 recharge-cum-production tube wells, locally known as *Holiyas*, were developed across the ten villages of Khadir Island during the period 2017–2021. These structures were implemented with support from the GEER Foundation and the Central Ground Water Board (CGWB).

Holiyas are designed to perform dual functions:

1. Artificial groundwater recharge during monsoon periods, and

2. Groundwater abstraction for domestic use during dry seasons.

These systems enhance aquifer recharge by allowing rainwater and surface runoff to infiltrate directly into deeper aquifer zones while simultaneously serving as decentralized drinking water sources. The recharge efficiency of these systems depends on lithology, lineament connectivity, soil permeability, and groundwater salinity conditions.

4.11.4 Small Khet Talavadi, Ponds and Lakes:

Small farm ponds locally known as *Khet Talavadi*, along with village ponds and seasonal lakes, are distributed throughout all ten villages of Khadir Island. These structures are primarily used for rainwater storage, livestock water supply, supplemental irrigation, and localized groundwater recharge.

These decentralized water harvesting systems are especially important in areas where groundwater quality is poor or saline. During monsoon seasons, these ponds capture runoff and help reduce immediate water scarcity. Infiltration from pond beds also contributes to shallow groundwater recharge where permeable alluvial materials are present.

4.11.5 Hydrogeological Significance:

Collectively, the existing water infrastructure of Khadir Island supports:

- Rainwater harvesting,
- Groundwater recharge,
- Salinity control,
- Localized aquifer recovery,
- Livestock water security,
- Domestic water supply sustainability.

However, despite these interventions, increasing groundwater salinity, declining recharge, over-extraction, and climate variability continue to threaten long-term water security within the island. Therefore, strengthening existing recharge structures, improving maintenance, promoting managed aquifer recharge, and adopting location-specific groundwater management strategies are essential for sustainable water resource development in Khadir Island.

4.12 Role of Field Data in Subsequent Chapters

The field data collected during these investigations are not merely descriptive; they serve as essential inputs and validation targets for the analytical and numerical work presented in the following chapters.

Table 4.11: Role of Field Data in Subsequent Chapters

Data Type	Chapter	Specific Use
Well inventory (8 wells)	Chapter 5	Validation of GWPZ map
pH, TDS, temperature (2019 and 2021)	Chapters 5 and 6	Baseline water quality; validation of seawater intrusion model
Lithological observations	Chapter 5	Conceptual model for MODFLOW-6 (layer definition, K zones)
Structural features (faults, dip)	Chapters 5 and 6	Lineament validation; structural control on groundwater flow
Cropping pattern	Chapter 6	Water demand assessment (irrigation requirements)
Infrastructure inventory	Chapters 3 and 7	Existing water resources; baseline for development plan
KC-13 and HPII_KCH_006 long-term data	Chapter 5	Seawater intrusion model calibration and validation

PART C: HYDROGEOLOGICAL ANALYSIS

4.13 HYDROGEOLOGY OF KHADIR ISLAND:

The hydrogeological framework of Khadir Island is controlled by lithology, geomorphology, structural features, recharge conditions, and seawater intrusion processes (Biswas, 2005; Maurya et al., 2013). The island contains a thin and fragile freshwater lens floating over saline groundwater under delicate hydrogeological equilibrium. Spatial analysis and long-term groundwater monitoring indicate a strong west–east variation in groundwater quality, recharge potential, and aquifer behaviour. The western part around Dholavira exhibits comparatively favourable groundwater conditions and recovery potential, whereas the eastern part around Kalyanpar is severely affected by salinity ingress and permanent seawater intrusion. The hydrogeological cross-section prepared from monitoring well data clearly demonstrates that groundwater quality is controlled not only by lithology, but also by structural permeability, recharge conditions, drainage characteristics, and groundwater abstraction patterns.

4.13.1 Shallow Aquifer System

The shallow aquifer system of Khadir Island is predominantly unconfined to semi-confined and occurs within the upper 30–50 m depth zone comprising weathered sandstone, clayey sand, and fractured sedimentary formations (Todd and Mays, 2005). The shallow aquifer forms the principal groundwater source for domestic consumption, livestock use, and limited irrigation activities throughout the island.

The uppermost hydrogeological unit corresponds to the Sandhan Formation (0–30 m), composed mainly of grey sandstone containing fossil wood fragments. This unit acts as a shallow unconfined aquifer and exhibits comparatively better groundwater occurrence in the western region. Beneath this layer lies the Jhurian Formation extending approximately from 30 m to 120–130 m depth. The formation consists of medium- to coarse-grained sandstone and constitutes the principal aquifer unit of the island due to its moderate to high permeability characteristics. In the western region near Dholavira, this aquifer contains comparatively better-quality groundwater, whereas in the eastern region near Kalyanpar the same aquifer becomes saline due to seawater intrusion and poor recharge conditions.

The lower part of the Jhurian Formation occurs approximately between 120/130 m and 180/200 m depth and consists mainly of silty sandstone. This zone behaves as a semi-confined layer that restricts vertical groundwater movement. Below this unit, the Jhuma Formation occurs between about 180/200 m and 300 m depth and is composed predominantly of limestone and shale. Due to negligible permeability, this formation behaves as an aquitard or aquiclude and limits deep groundwater circulation. Basement rocks comprising granite and gneiss occur below approximately 300 m depth.

Groundwater levels within the shallow aquifer exhibit marked spatial variability. In the western part near Dholavira, Ratanpar, and Janan, groundwater levels generally occur at shallow depths ranging from approximately 2–10 m below ground level (mbgl). In contrast, groundwater levels in the eastern region near Kalyanpar and Gadhada occur at greater depths ranging from about 10–20 mbgl because of poor recharge conditions and groundwater stress (CGWB, 2020). The overall groundwater flow direction is from the relatively elevated eastern region toward the western and southern margins of the island.

Hydrogeological comparison between the two long-term monitoring wells further highlights the spatial contrast in groundwater conditions across the island. The Dholavira monitoring well (KC-13) located in the western groundwater potential zone exhibits comparatively low TDS values (~1,500–2,700 mg/L), better recharge conditions, and partial groundwater recovery following monsoon recharge. In contrast, the Kalyanpar monitoring well (HP11_KCH_006) located in the eastern region consistently exhibits high TDS concentrations (>4,000–7,000 mg/L), poor groundwater quality, and persistent seawater intrusion conditions. Na^+/Cl^- ratios below 0.86 in the eastern region indicate active seawater mixing and salinization processes (Freeze and Cherry, 1979).

The hydrogeological cross-section further demonstrates that lithology alone does not determine groundwater quality. Structural controls such as faults, fractures, and lineaments significantly influence groundwater movement and recharge conditions (Sander, 2007; Magowe and Carr, 1999). Similarly, recharge potential is strongly controlled by surface and terrain characteristics including slope, drainage density, alluvial plains, and soil permeability. The western region exhibits comparatively favourable recharge conditions because of higher lineament density, lower drainage density, flatter terrain, and better infiltration characteristics. Conversely, the eastern region is characterized by poor recharge conditions, higher salinity, and permanent seawater intrusion due to clayey formations, low structural permeability, and continuous groundwater stress.

4.13.2 Deep Aquifer Potential

Below the shallow aquifer system, deeper confined aquifers may occur within fractured sandstone formations and buried palaeochannel deposits at depths ranging approximately between 100 m and 200 m. Studies conducted in the northern Great Rann of Kachchh have identified buried palaeochannels containing medium- to coarse-grained sand deposits capable of yielding artesian or semi-artesian groundwater flow (Bhadra et al., 2021).

These buried palaeochannel systems may serve as potential freshwater reservoirs because deeper sand bodies generally possess higher permeability and reduced interaction with saline shallow groundwater (Fetter, 2018). The hydrogeological cross-section suggests that deeper groundwater movement may occur within confined sandstone horizons beneath the semi-confined Jhurian layer. However, no dedicated deep exploratory borehole has yet been drilled on Khadir Island specifically to investigate the occurrence and characteristics of palaeochannel aquifers. Consequently, the spatial extent, hydraulic properties, recharge behaviour, and groundwater quality of deep confined aquifers remain uncertain.

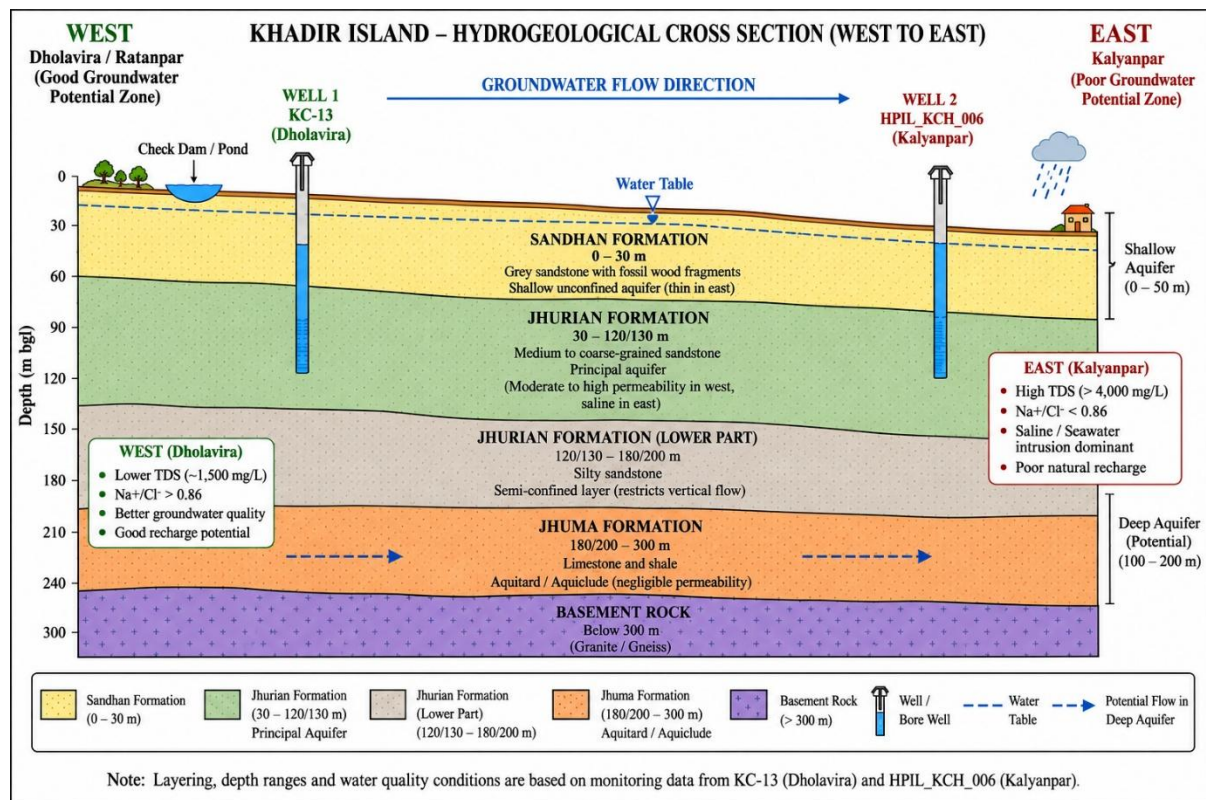


Figure 4.19: Conceptual hydrogeological cross-section of Khadir Island from west (Dholavira) to east (Kalyanpar) showing generalized stratigraphy, aquifer configuration, groundwater flow direction, and groundwater quality variation (not to scale).

The scientific exploration of deep palaeochannel aquifers therefore represents an important priority for future hydrogeological investigations and sustainable groundwater development within the Great Rann of Kachchh.

4.14 GROUNDWATER RECHARGE

Groundwater recharge on Khadir Island occurs predominantly during the southwest monsoon season through infiltration of rainfall, runoff ponding, streamflow infiltration, and recharge from water harvesting structures (Healy and Cook, 2002). Because annual potential evapotranspiration greatly exceeds annual rainfall, effective recharge occurs only during intense rainfall events capable of overcoming evapotranspiration and runoff losses (IMD, 2022).

Recharge estimation carried out using the Water Table Fluctuation (WTF) method indicates that the average annual recharge is approximately 602 mm over the effective recharge area, which covers nearly 90% of the island. However, recharge exhibits extremely high temporal variability due to fluctuating monsoon rainfall conditions. During the wet monsoon year of 2011, recharge exceeded approximately 1,100 mm, whereas during the drought year of 2018 recharge declined to nearly 155 mm.

Recharge distribution across the island is highly uneven. The western region around Ratanpar, Janan, and Dholavira exhibits comparatively higher recharge because of sandy and permeable soils, moderate slopes, lower drainage density, higher lineament density, and favourable alluvial recharge conditions (Jha et al., 2007). In contrast, the eastern region near Kalyanpar and Gadhada exhibits lower recharge rates because clayey soils, steeper slopes, shale formations, and poor structural permeability promote surface runoff rather than infiltration.

Field observations further indicate that check dams, ponds, recharge shafts, and Holiya structures contribute significantly to localized recharge enhancement during monsoon periods (GEER Foundation, 2021). Managed aquifer recharge therefore represents an important strategy for improving groundwater sustainability within the island.

4.15 GROUNDWATER ABSTRACTION

Groundwater abstraction on Khadir Island occurs primarily from the shallow aquifer system through dug wells, hand pumps, bore wells, livestock wells, and recharge-cum-production tube wells. Groundwater constitutes the principal source of freshwater for domestic

consumption, livestock requirements, agriculture, tourism activities, and local livelihoods across the island (Government of Gujarat, 2020).

According to the Gujarat Water Resources Development Corporation (GWRDC) groundwater census, approximately 4,495 groundwater abstraction structures are present within Khadir Island. These include around 1,245 irrigation wells, 2,800 domestic hand pumps, and 450 livestock wells (GWRDC, 2020).

The total annual groundwater abstraction is estimated to be approximately 1,257 ML, which corresponds to nearly 72% of the average annual renewable groundwater resource. Such high groundwater dependence places considerable stress on the shallow freshwater lens and increases the risk of groundwater depletion and seawater intrusion.

Long-term groundwater monitoring data indicate that excessive abstraction has already resulted in groundwater quality deterioration and temporary aquifer collapse in some areas, particularly around Dholavira during 2015. Over-extraction lowers freshwater hydraulic head, allowing saline groundwater to migrate landward and upward according to the Ghyben–Herzberg principle (Freeze and Cherry, 1979).

Therefore, sustainable groundwater management in Khadir Island requires controlled groundwater abstraction, artificial recharge enhancement, protection of recharge zones, alternative water supply development, and community-based groundwater governance. These measures are essential for preventing irreversible aquifer salinization and ensuring long-term water security within the fragile island ecosystem.

4.16 KEY FINDINGS AND INTEGRATED INTERPRETATION:

The major results and their implications from the study-area assessment and field investigations are summarised below:

- **Climatic and hydrological conditions:** Khadir Island experiences a highly water-deficit climatic regime, with annual rainfall of approximately **420 mm** against potential evapotranspiration of about **2,140 mm/year**. The low and variable rainfall limits natural groundwater recharge and contributes to dependence on groundwater resources.
- **Geological and hydrogeological controls:** Groundwater occurrence is strongly influenced by the combined effects of **lithology, geomorphology, structural features, soil characteristics and recharge conditions**. The western part, particularly around Dholavira, exhibits comparatively favourable groundwater conditions, whereas the eastern sector around Kalyanpar shows persistent salinity and less favourable recharge conditions.
- **Recharge characteristics:** Permeable sandy zones provide relatively better infiltration opportunities, while clay-rich and saline soils restrict infiltration. Existing ponds, Khet Talavadis, seasonal water bodies, check dams and Holiyas provide localised storage and recharge, but their contribution is insufficient to meet the overall water requirements of the island.
- **Groundwater-level and quality variation:** Long-term observations demonstrate significant spatial and temporal variation in groundwater conditions. At Dholavira (KC-13), the groundwater level declined from approximately **5.95 m to 10.20 m**, and the well became dry around 2015. During the same period, TDS increased from approximately **1,220 to 8,875 mg/L**, followed by partial recovery. In contrast, the Kalyanpar monitoring well remained highly saline, with TDS of approximately **7,200 mg/L** and chloride concentration of approximately **4,200 mg/L**.
- **Groundwater abstraction and stress:** The island has approximately **4,495 groundwater abstraction structures**, with estimated annual abstraction of about **1,257 ML**. The dependence of domestic, agricultural, livestock and tourism activities on groundwater places considerable pressure on the shallow freshwater system, particularly under limited recharge conditions.
- **Field-investigation evidence:** Field investigations conducted during **2019 and 2021** confirmed substantial differences in groundwater availability, water quality, recharge conditions and existing water infrastructure across the island. The observations also

provide ground-based evidence for the spatial variation identified through subsequent analytical approaches.

- **Integrated interpretation:** The combined findings indicate that Khadir Island represents a **spatially heterogeneous and hydrogeologically vulnerable groundwater system**, with comparatively favourable conditions in parts of the western sector and persistent salinity constraints in the eastern sector.
- **Implication for water-resource development:** The results highlight the need for **location-specific groundwater assessment, regulated abstraction, recharge enhancement, continuous groundwater-quality monitoring and development of supplementary water resources**. These field-based findings provide the foundation for the groundwater potential assessment, numerical modelling, seawater-intrusion assessment, MAR planning and integrated water-resource development proposed in the subsequent chapters.

4.17 SUMMARY OF THE STUDY AREA AND FIELD INVESTIGATIONS

Khadir Island, covering approximately **315 km²** within the Great Rann of Kachchh (GRK), represents a fragile hydrogeological environment characterized by hyper-arid climatic conditions, limited freshwater availability, and saline groundwater. The island receives approximately **420 mm/year of highly variable rainfall**, while potential evapotranspiration is about **2,140 mm/year**, resulting in a persistent water deficit and limited natural groundwater recharge (IMD, 2022; Allen et al., 1998).

Geologically, the island comprises predominantly **clayey sand, shale, sandstone, and limestone**, with the **Pink Sandstone of the Kanakavati Formation** serving as the principal aquifer unit. Groundwater conditions are controlled by the combined influence of lithology, geomorphology, structural features, soil characteristics, and recharge conditions. The western sector, particularly around Dholavira, exhibits comparatively favourable groundwater conditions, whereas the eastern sector around Kalyanpar and Gadhada is characterized by poor recharge conditions and severe salinity (Biswas, 2005; Sander, 2007).

The groundwater system consists of a relatively thin **freshwater lens of about 15–25 m thickness** overlying saline groundwater. Groundwater quality generally deteriorates from west to east, with Dholavira showing comparatively better quality and recovery potential, while Kalyanpar and Gadhada exhibit persistent salinity and seawater-intrusion impacts. This spatial variability highlights the sensitivity of the freshwater resource to recharge conditions, structural

controls, groundwater abstraction, and salinity processes (Freeze and Cherry, 1979; Todd and Mays, 2005).

The island supports approximately **17,000 people across ten villages**, with pastoralism, agriculture, handicrafts, and tourism forming the major livelihood activities. Existing water resources and infrastructure include seasonal rivers and streams, check dams, Holiyas, village ponds, lakes, Khet Talavadis, and traditional rainwater-harvesting systems. The Manhar and Mansar drainage systems, together with check dams at Ganeshpar and Amrapar and approximately 30 Holiyas, provide localized storage and recharge. However, these resources remain insufficient to satisfy the increasing water requirements of the island. Field investigations undertaken during **2019 and 2021** across representative villages, including Dholavira, Ratanpar, Janan, Ganeshpar, Amrapar, Kalyanpar, and Gadhada, provided ground-truth information on groundwater levels, well characteristics, lithology, structural features, groundwater quality, land use, recharge infrastructure, and socio-economic conditions. **Eight representative wells** were inventoried and monitored, supplemented by long-term observation-well data from CGWB and GWRDC.

Overall, the field evidence indicates **substantial spatial and temporal variability in groundwater conditions**, accompanied by falling groundwater levels, increasing salinity, seasonal well failures, declining surface-water storage, and progressive seawater-intrusion impacts. The contrasting conditions between the relatively favourable western sector and the saline eastern sector demonstrate the need for **location-specific groundwater assessment, recharge enhancement, regulated abstraction, groundwater-quality monitoring, and supplementary water-resource development**. The findings of this chapter provide the essential field and hydrogeological basis for the groundwater potential assessment, numerical modelling, seawater-intrusion analysis, and integrated water-resource planning presented in the subsequent chapters.

HYDROGEOLOGICAL ASSESSMENT AND GROUNDWATER MANAGEMENT STRATEGY FOR KHADIR ISLAND

"From potential to protection: integrating groundwater zoning, flow modelling, intrusion assessment, and managed recharge for sustainable island aquifer management"

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5.1 INTRODUCTION

This chapter constitutes the core analytical work of the thesis, integrating four interconnected components into a single comprehensive assessment of the hydrogeological system of Khadir Island and the strategies required for its sustainable management. The chapter is organised into four distinct but sequentially linked parts.

Part A: Groundwater Potential Zoning (GWPZ) applies the Multi-Influencing Factor (MIF) method integrated with remote sensing and geographic information systems (RS-GIS) to delineate areas of varying groundwater potential across Khadir Island. The resulting GWPZ map classifies the island into Good, Moderate, and Poor zones based on the combined influence of eight controlling factors: lithology, geomorphology, lineament density, rainfall, slope, drainage density, land use/land cover, and soil type. The GWPZ classification is validated using long-term hydrochemical data from government monitoring wells.

Part B: Groundwater Flow Modelling and Zone Budget presents the development, calibration, and results of a transient three-dimensional groundwater flow model using MODFLOW-6 within the ModelMuse 4.4.3 environment. The model simulates hydraulic heads and fluxes across four hydrostratigraphic layers for the period 2001–2020. A zone budget analysis quantifies the volumetric exchanges between layers and across boundaries, providing critical insights into recharge mechanisms, aquifer behaviour, and the sustainability of current abstraction patterns.

Part C: Seawater Intrusion Assessment employs a density-dependent sharp-interface model (SWI2 package) to simulate the progression of the saline front from the coastline into the freshwater lens over the 20-year simulation period. The model identifies a critical intrusion threshold, evaluates the sensitivity of the system to key parameters, and is validated using independent hydrogeochemical indicators including Na^+/Cl^- ratios and TDS trends.

PART A: GROUNDWATER POTENTIAL ZONING (GWPZ)

5.2 THEMATIC LAYERS FOR GROUNDWATER POTENTIAL MAPPING

Groundwater potential zoning (GWPZ) is the process of delineating areas with varying capacity to store and transmit groundwater based on multiple controlling factors. In arid and semi-arid regions, where direct field investigations are expensive and time-consuming, remote sensing (RS) and geographic information systems (GIS) provide a cost-effective and spatially explicit alternative (Jha et al., 2007; Magesh et al., 2012). By integrating multiple thematic layers in a GIS environment, it is possible to classify the landscape into zones of Good, Moderate, and Poor groundwater potential based on the combined weight of the controlling factors.

5.2.1 Selection of Thematic Layers

Eight thematic layers were selected for GWPZ mapping based on their documented influence on groundwater occurrence, recharge, and movement in arid and semi-arid environments (Magesh et al., 2012; Das and Pardeshi, 2018; Arulbalaji et al., 2019). The selected layers are:

1. **Lithology:** Controls primary porosity and permeability, determining the aquifer's ability to store and transmit water.
2. **Geomorphology:** Reflects landform evolution and indicates the relative potential for infiltration versus runoff.
3. **Lineament Density:** Represents secondary porosity from fractures, faults, and joints, which act as preferential pathways for groundwater movement.
4. **Rainfall:** Provides the primary water input to the groundwater system through infiltration and recharge.
5. **Slope:** Controls the partitioning of precipitation between surface runoff and infiltration.
6. **Drainage Density:** Inversely related to permeability; areas of low drainage density typically indicate high infiltration capacity.
7. **Land Use/Land Cover (LULC):** Affects surface conditions that influence infiltration, runoff, and evapotranspiration.

8. **Soil Type:** Governs the infiltration capacity of the land surface and the movement of water from the surface to the water table.

Each thematic layer was prepared in ArcGIS 10.8 using the data sources and procedures described in Chapter 3. The layers were converted to raster format with a uniform cell size of 30 m × 30 m, classified into sub-classes based on hydrogeological significance, and assigned ratings on a scale of 1–10, with higher values indicating greater contribution to groundwater potential. The spatial distribution of each thematic layer has been presented and discussed in detail in Chapter 4.

5.2.2 Feature Ratings

Feature ratings were assigned to individual subclasses of the thematic layers in order to represent their relative suitability for groundwater occurrence and recharge potential. A common rating scale ranging from 1 to 10 was adopted, where higher ratings indicate more favourable hydrogeological conditions for groundwater infiltration, storage, and movement, while lower ratings represent unfavourable conditions with poor recharge characteristics. The ratings were assigned based on published literature, hydrogeological principles, field observations, and the specific environmental conditions of Khadir Island (Magesh et al., 2012; Das and Pardeshi, 2018).

For the lithology layer, Kanakavati sandstone and Jhurio shell-limestone received the highest ratings because of their comparatively higher permeability, porosity, and groundwater storage capacity. In contrast, Khari shale and sandy shale were assigned lower ratings due to their low permeability and aquitard behaviour. Clayey sand received moderate ratings because it supports infiltration but remains vulnerable to salinity ingress.

In the geomorphology layer, alluvial plains and weathered or fractured pediplains were assigned high ratings because they favour infiltration and groundwater recharge. Structural hills and denudational hills received low ratings owing to higher runoff and limited infiltration potential. Water bodies were assigned relatively high ratings because they contribute to localized recharge.

Lineament density was considered an important indicator of secondary permeability and groundwater movement. Areas with very high and high lineament density received higher ratings because fractures and faults act as preferential pathways for groundwater flow and storage. Conversely, areas with low lineament density were assigned lower ratings due to limited structural control on groundwater occurrence.

Table 5.1: Feature Ratings for Thematic Layers (1–10 Scale)

Factor	Feature Class	Rating
Lithology	Kanakavati sandstone	9
	Jhurio shell-limestone	8
	Clayey sand	6
	Sandy shale	4
	Khari shale	2
Geomorphology	Alluvial plain	9
	Pediplain (weathered/fractured)	8
	Water bodies	7
	Pediplain (moderate)	5
	Structural hills	3
	Denudational hills	2
Lineament Density	Very high (>1.5 km/km ²)	9
	High (1.2–1.5 km/km ²)	8
	Medium (0.9–1.2 km/km ²)	6
	Low (0.6–0.9 km/km ²)	4
	Very low (<0.6 km/km ²)	2
Rainfall	>450 mm	9
	350–450 mm	7
	<350 mm	5
Slope	Flat (0–2°)	9
	Gentle (2–5°)	8
	Moderate (5–10°)	6
	Steep (10–15°)	4
	Very steep ($>15^\circ$)	2
Drainage Density	Very low (<0.5 km/km ²)	9
	Low (0.5–1.0 km/km ²)	8
	Medium (1.0–1.5 km/km ²)	6
	High (1.5–2.0 km/km ²)	4
	Very high (>2.0 km/km ²)	2
LULC	Water bodies	9
	Agricultural land	8
	Grassland/grazing land	6
	Built-up/wasteland	3
Soil Type	Coarse loamy (high infiltration)	9
	Fine loamy (moderate infiltration)	7
	Clayey (low infiltration)	4

Rainfall classes were rated according to their contribution to recharge potential. Higher rainfall zones received higher ratings because increased precipitation enhances infiltration and

recharge opportunities, whereas lower rainfall zones were assigned comparatively lower ratings.

Slope ratings were assigned inversely with terrain steepness. Flat and gentle slopes received high ratings because they promote infiltration and reduce runoff velocity, while steep and very steep slopes received low ratings due to rapid runoff and limited recharge opportunity.

For drainage density, areas with very low and low drainage density were assigned higher ratings because lower drainage density indicates greater infiltration and reduced surface runoff. In contrast, areas with high drainage density received lower ratings as they favour rapid runoff and reduced groundwater recharge.

Within the LULC layer, water bodies and agricultural land received higher ratings because they contribute directly or indirectly to groundwater recharge. Grassland and grazing land received moderate ratings, whereas built-up areas and wasteland received low ratings because impervious surfaces and barren terrain reduce infiltration capacity.

For soil type, coarse loamy soils received the highest ratings due to their high infiltration capacity and favourable recharge conditions. Fine loamy soils were assigned moderate ratings, while clayey soils received lower ratings because of their poor permeability and low infiltration characteristics.

The assigned feature ratings collectively represent the hydrogeological suitability of each thematic layer and form the basis for the weighted overlay analysis used in groundwater potential zonation.

5.3 MULTI-INFLUENCING FACTOR (MIF) ANALYSIS AND WEIGHTED OVERLAY

5.3.1 Inter-Relationship Matrix

The Multi-Influencing Factor (MIF) method was employed to determine the relative importance of the thematic layers controlling groundwater occurrence on Khadir Island. The MIF approach is based on the concept that groundwater potential is governed not by a single factor, but by the combined interaction of multiple hydrogeological, geomorphological, climatic, and land-surface parameters (Magesh et al., 2012; Das and Pardeshi, 2018).

In this method, each thematic layer is evaluated according to its influence on other controlling factors. These relationships are categorized into two types:

- **Major influence** (assigned a score of 1.0)
- **Minor influence** (assigned a score of 0.5)

The inter-relationship matrix was developed using published literature, hydrogeological principles, field observations, and expert interpretation specific to the environmental conditions of Khadir Island. Eight thematic layers—Lithology, Geomorphology, Lineament Density, Rainfall, Slope, Drainage Density, Land Use/Land Cover (LULC), and Soil Type—were considered in the analysis.

Lithology influences groundwater occurrence through porosity, permeability, and aquifer characteristics, while geomorphology controls infiltration, runoff, and recharge conditions. Lineament density represents secondary permeability created by fractures and faults, which act as preferential pathways for groundwater movement. Rainfall serves as the primary climatic input controlling recharge availability. Slope and drainage density govern runoff versus infiltration relationships, whereas LULC and soil type influence infiltration capacity, evapotranspiration, and surface recharge conditions.

Table 5.2: Inter-Relationship Matrix for MIF Analysis

Factor	Major Influences	Minor Influences	Major Count	Minor Count
Lithology	—	Geomorphology, Lineament, Soil	0	3
Geomorphology	Lithology	Slope, Drainage, LULC	1	3
Lineament Density	Lithology, Geomorphology	Drainage	2	1
Rainfall	—	—	0	0
Slope	Geomorphology	Drainage, LULC	1	2
Drainage Density	Slope, Geomorphology, Lineament	LULC	3	1
LULC	Geomorphology, Soil	Slope, Drainage	2	2
Soil Type	Lithology, Geomorphology	LULC	2	1

Rainfall was considered an independent factor in the MIF analysis because it acts mainly as the primary climatic input supplying water for recharge, but it does not directly control the spatial characteristics of lithology, geomorphology, slope, drainage density, lineament density, soil type, or LULC within the study area (Magesh et al., 2012; Das and Pardeshi, 2018). In Khadir Island, the spatial variation of rainfall is relatively low compared to the strong influence of terrain and hydrogeological factors on groundwater occurrence. Therefore, rainfall was assigned no major or minor inter-relationship in the MIF matrix, although a minimum base weight was provided to acknowledge its importance in groundwater recharge.

The inter-relationship matrix indicates that Drainage Density exerts the strongest influence on other factors because it directly controls runoff concentration, infiltration opportunity, and recharge potential. Similarly, LULC, Geomorphology, Lineament Density, and Soil Type show significant interaction with other thematic layers, highlighting their major role in groundwater occurrence within the arid terrain of Khadir Island.

5.3.2 Weight Calculation

The relative weight of each thematic layer was calculated from the inter-relationship matrix using the standard MIF weighting formula:

$$\text{Weight} = [(M \times 1.0) + (m \times 0.5)] / \Sigma[(M \times 1.0) + (m \times 0.5)] \times 100$$

where M is the number of major influences and m is the number of minor influences.

A minimum base weight of 1.0 was assigned to Rainfall to acknowledge its role as the primary water input, even though it exerts no direct influence on other factors. Table 5.3 presents the calculated weights.

The analysis reveals that Drainage Density received the highest weight (22.6%), reflecting its critical control on runoff versus infiltration in this arid setting. Drainage density is inversely related to permeability: areas with very low drainage density indicate high infiltration capacity and consequently high groundwater potential, whereas areas of high drainage density indicate low permeability, high runoff, and poor groundwater conditions.

LULC ranked second (19.4%), highlighting the significant impact of land use on recharge. Agricultural land and water bodies enhance recharge by providing surfaces conducive to infiltration, whereas built-up areas and wasteland limit infiltration and promote runoff.

The combined weight of Geomorphology, Lineament Density, and Soil Type (48.3% total) demonstrates the importance of physical land-surface characteristics in controlling

groundwater occurrence. These three factors together account for nearly half of the total weight, underscoring their collective influence.

Table 5.3: Calculated MIF Weights for Eight Thematic Layers

Factor	Score ($M \times 1 + m \times 0.5$)	Weight (%)
Drainage Density	3.5	22.6
LULC	3.0	19.4
Geomorphology	2.5	16.1
Lineament Density	2.5	16.1
Soil Type	2.5	16.1
Slope	2.0	12.9
Lithology	1.5	9.7
Rainfall	1.0	6.5
Total	15.5	100

Slope (12.9%), Lithology (9.7%), and Rainfall (6.5%) received relatively lower weights, reflecting their more indirect or spatially uniform influence in the Khadir Island context. The relatively low weight for rainfall is appropriate because, over the limited spatial extent of the island (315 km²), rainfall variation is modest (380–450 mm/year), and other factors exert stronger spatial control on groundwater potential.

5.3.3 Weighted Overlay Analysis

The weighted overlay analysis was carried out in ArcGIS 10.8 by integrating the eight reclassified thematic layers using the MIF-derived weights. Each raster layer was multiplied by its respective normalized weight and combined to generate the Groundwater Potential (GWP) index map.

$$\text{GWP_MIF} = \sum (R_i \times W_i)$$

where R_i is the rating of feature class i and W_i is the weight of layer i expressed as a decimal (e.g., 0.226 for Drainage Density).

The final groundwater potential index map represents the cumulative hydrogeological suitability of each location for groundwater occurrence and recharge. Higher index values indicate favourable groundwater conditions, whereas lower values represent poor recharge and groundwater potential.

The generated groundwater potential map was classified into three categories:

- Good Groundwater Potential
- Moderate Groundwater Potential
- Poor Groundwater Potential

Classification was performed using the Natural Breaks (Jenks) method (Jenks, 1967), which minimizes variance within classes and maximizes variance between classes. The Jenks classification method was preferred over equal interval and quantile approaches because it identifies natural groupings within the data distribution, thereby providing a more realistic representation of spatial groundwater potential variations across Khadir Island.

5.4 GROUNDWATER POTENTIAL ZONES OF KHADIR ISLAND

The final Groundwater Potential Zone (GWPZ) map of Khadir Island was prepared using the Multi-Influencing Factor (MIF) weighted overlay method in ArcGIS 10.8. The classification was carried out using the Natural Breaks (Jenks) method (Jenks, 1967). Based on the integrated influence of lithology, geomorphology, lineament density, rainfall, slope, drainage density, LULC, and soil type, the island was classified into three categories: **Good**, **Moderate**, and **Poor** groundwater potential zones.

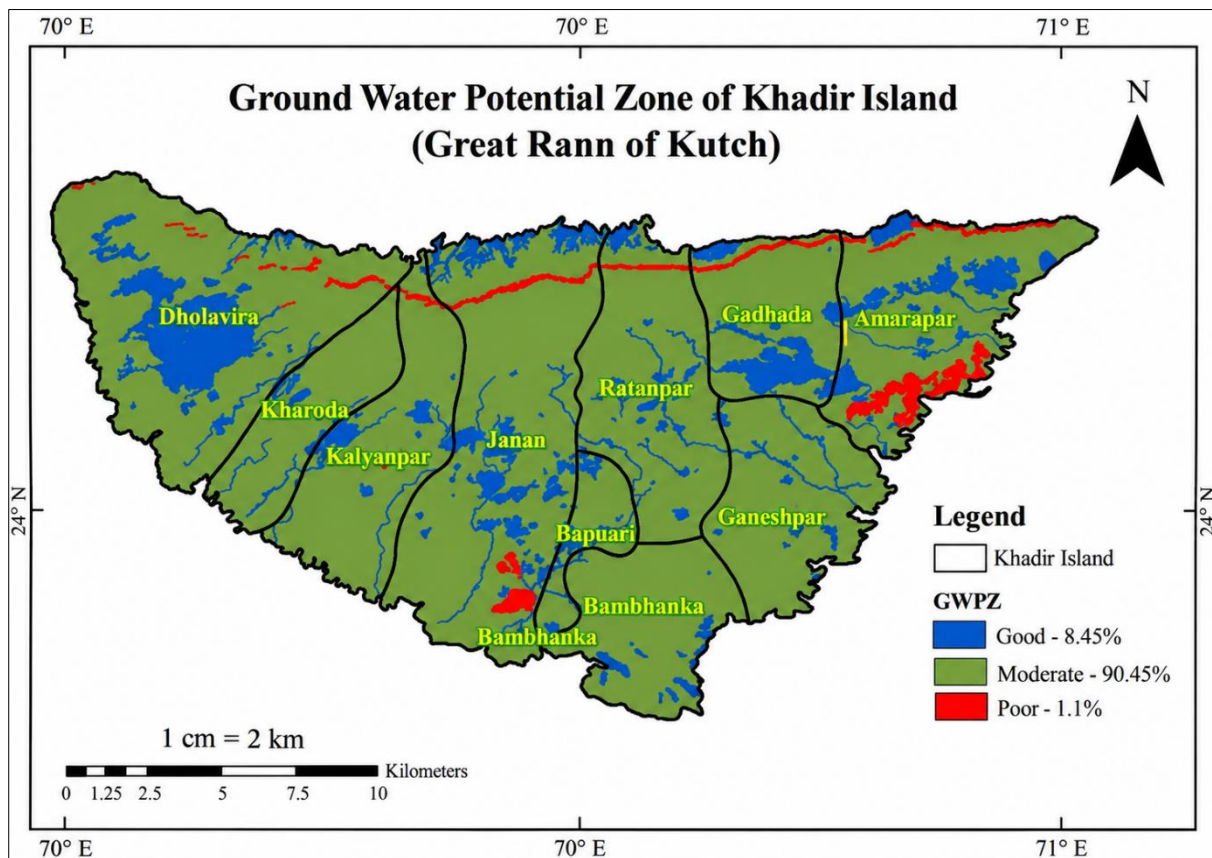


Figure 5.1: Groundwater Potential Zone Map of Khadir Island

Table 5.4: Areal Distribution of Groundwater Potential Zones

GWPZ Class	Area (km²)	Percentage (%)	Villages Covered
Good	26.65	8.45	Ratanpar, Janan, Dholavira (western part)
Moderate	285.10	90.45	Central and eastern villages; Amrapar, Ganeshpar, Bambhanka, Kharoda, Bapuari, Dholavira (eastern part)
Poor	3.45	1.10	Kalyanpar, Gadhada (eastern part)
Total	315.20	100.00	

5.4.1 Good Potential Zone

The Good zone occupies 26.65 km² (8.45% of the island) and is concentrated in the western part, covering the villages of Ratanpar, Janan, and the western portion of Dholavira. This zone is characterised by a favourable combination of hydrogeological conditions:

- **Permeable lithology:** Underlain by Kanakavati sandstone and clayey sand, which have moderate to high infiltration capacity and form the principal aquifer unit of the island.
- **Favourable geomorphology:** Dominated by alluvial plains and weathered/fractured pediplain, which promote infiltration and provide storage for recharged water.
- **High lineament density (>1.2 km/km²):** The high concentration of fractures and faults enhances secondary permeability, creating preferential pathways for vertical recharge and lateral groundwater movement.
- **Flat to gentle slopes (0–5°):** The nearly level terrain minimises surface runoff and maximises the residence time of rainwater at the surface, allowing greater opportunity for infiltration.
- **Very low drainage density (<0.5 km/km²):** The sparse drainage network indicates that most rainfall infiltrates rather than running off, confirming the high permeability of the surface materials.
- **Favourable LULC:** Agricultural land and grassland dominate, providing surfaces that are conducive to infiltration compared to built-up or barren areas.
- **Coarse to fine loamy soils:** These soils have moderate to high infiltration capacity, facilitating the downward movement of water to the water table.

The Good zone represents the most valuable groundwater resource on Khadir Island. Wells in this zone are expected to have higher yields, better water quality, and greater resilience to

drought. The presence of the Good zone in the western part of the island aligns with the independent evidence from long-term monitoring well KC-13 at Dholavira, which historically had good water quality and has demonstrated recovery potential even after severe salinity stress.

5.4.2 Moderate Potential Zone

The Moderate zone is the dominant class, occupying 285.10 km² (90.45% of the island) and covering the central and eastern parts, including Amrapar, Ganeshpar, Bambhanka, Kharoda, Bapuari, and the eastern portions of Dholavira. This zone is characterised by:

- **Mixed lithology:** Clayey sand with interbedded shale, providing moderate to low primary permeability.
- **Piediplain geomorphology:** The weathered piediplain surface provides moderate infiltration conditions, but the underlying shale layers restrict deeper percolation.
- **Moderate lineament density (0.9–1.2 km/km²):** Some secondary permeability from fractures, but less than in the Good zone.
- **Gentle to moderate slopes (2–10°):** Some runoff generation occurs, reducing the proportion of rainfall that contributes to recharge.
- **Moderate drainage density (1.0–1.5 km/km²):** A more developed drainage network indicates a greater tendency for runoff compared to the Good zone.
- **Mixed LULC:** A combination of agriculture, rangeland, and some built-up areas.
- **Fine loamy to clay loam soils:** Moderate to low infiltration capacity.

The Moderate zone supports the majority of the island's population and agricultural activities. While groundwater is available, yields are lower and water quality is more variable than in the Good zone. Sustainable management of this zone is critical, as it represents the largest area and the primary living space for the island's communities.

5.4.3 Poor Potential Zone

The Poor zone occupies only 3.45 km² (1.10% of the island) and is confined to small patches in the eastern part, covering the villages of Kalyanpar and Gadhada. This zone is characterised by:

- **Low-permeability Khari shale:** The shale acts as an effective aquitard, restricting both vertical recharge and lateral groundwater movement.
- **Structural and denudational hills:** These geomorphic units have steep slopes that generate high runoff and negligible infiltration.

- **Low to very low lineament density ($<0.9 \text{ km/km}^2$):** Limited secondary permeability from fractures.
- **Moderate to steep slopes ($5\text{--}30^\circ$):** High runoff generation with minimal opportunity for infiltration.
- **High to very high drainage density ($>1.5 \text{ km/km}^2$):** The well-developed drainage network indicates low permeability and high runoff.
- **Built-up/wasteland LULC:** Limited infiltration due to impervious surfaces and compacted ground.
- **Clayey soils:** Very low infiltration capacity.

The Poor zone is hydrogeologically unfavourable for groundwater development. The combination of impermeable lithology, steep slopes, high runoff, and limited recharge creates conditions of permanent water scarcity. This zone is also the area most severely affected by seawater intrusion, as demonstrated in Part C of this chapter. The poor groundwater potential in the eastern part is confirmed by the persistently high TDS and low Na^+/Cl^- ratios observed in monitoring well HP11_KCH_006 at Kalyanpar.

5.5 VALIDATION OF GWPZ USING HYDROCHEMICAL DATA

The GWPZ map was validated using long-term hydrochemical data from two government monitoring wells: KC-13 at Dholavira (located in the good zone) and HP11_KCH_006 at Kalyanpar (located in the Poor zone). Hydrochemical validation is a well-established method for confirming groundwater potential classifications, particularly in coastal and saline environments where water quality is a direct indicator of aquifer conditions (Mehmood et al., 2020; Li et al., 2020).

5.5.1 Expected Water Quality by GWPZ Class

Based on the GWPZ map, the two wells were expected to exhibit contrasting water quality characteristics:

- **KC-13 (Dholavira) – Good zone:** Expected to have low to moderate TDS, low chloride concentrations, and Na^+/Cl^- ratios greater than 0.86, indicating freshwater dominance with limited seawater influence.
- **HP11_KCH_006 (Kalyanpar) – Poor zone:** Expected to have high TDS, high chloride concentrations, and Na^+/Cl^- ratios less than 0.86, indicating active seawater mixing and saline conditions.

5.5.2 Observed Hydrochemical Data

Table 5.5 presents the long-term hydrochemical data for the two monitoring wells at 5-year intervals.

Table 5.5: Long-Term Hydrochemical Data for Validation Wells

Well ID	Year	Avg TDS (mg/L)	Avg Cl ⁻ (mg/L)	Na ⁺ /Cl ⁻ (calculated)	Status
KC-13 (Dholavira) – Good Zone	1995	1,220	120	~1.0 (fresh)	Good quality
	2005	4,555	2,340	~0.65	Saline intrusion began
	2010	8,875	4,760	~0.62	Very high salinity
	2015	Dry	Dry	—	Well dry
	2020	2,720	1,000	~0.90	Recovered, moderate salinity
HPII_KCH_006 (Kalyanpar) – Poor Zone	2015	7,170	4,140	~0.58	High salinity
	2020	7,250	4,300	~0.56	Persistent high salinity

5.5.3 Validation Outcome

The hydrochemical data strongly support the GWPZ classification:

- KC-13 (Dholavira) – Good Zone:** The well historically had good water quality (TDS 1,220 mg/L in 1995, Na⁺/Cl⁻ ≈ 1.0), consistent with its location in the good groundwater potential zone. Although the well experienced severe salinity deterioration between 2005 and 2015—reflecting the island-wide seawater intrusion documented in Part C of this chapter—it demonstrated recovery potential. By 2020, TDS had declined to 2,720 mg/L and the Na⁺/Cl⁻ ratio had recovered to approximately 0.90, indicating a return to freshwater-dominant conditions. This recovery confirms that the western part of Khadir Island retains good groundwater potential and that the aquifer in this area is capable of responding positively to reduced abstraction or enhanced recharge.
- HPII_KCH_006 (Kalyanpar) – Poor Zone:** The well consistently shows very high TDS (7,170–7,250 mg/L) and chloride concentrations (4,140–4,300 mg/L), with Na⁺/Cl⁻ ratios (~0.57) well below the seawater threshold of 0.86. These values indicate

active and permanent seawater intrusion. The water quality never improves to potable levels, and there is no evidence of recovery between monitoring periods. This persistent saline condition confirms the Poor GWPZ classification and indicates that the eastern part of Khadir Island is in a state of chronic, possibly irreversible, seawater intrusion.

5.5.4 Quantitative Validation

The quantitative contrast between the two zones is striking:

- The Poor zone well has **66% higher TDS** than the Good zone well (7,250 vs. 2,720 mg/L in 2020).
- The Poor zone well has **330% higher chloride** than the Good zone well (4,300 vs. 1,000 mg/L in 2020).
- The Poor zone well consistently shows Na^+/Cl^- ratios **below 0.86**, while the Good zone well has recovered to a ratio **above 0.86**.

This large difference, combined with the fact that the Poor zone well never shows $\text{Na}^+/\text{Cl}^- > 0.86$, provides strong quantitative support for the GWPZ classification. The validation demonstrates that the MIF-based GWPZ map successfully captures the spatial variability in groundwater conditions across Khadir Island.

PART B: GROUNDWATER FLOW MODELLING AND ZONE BUDGET

5.6 CONCEPTUAL HYDROGEOLOGICAL MODEL

5.6.1 Regional Geological Setting

The development of a reliable groundwater flow model requires a sound conceptual understanding of the aquifer system. The conceptual hydrogeological model for Khadir Island was developed based on the geological framework of the Kachchh sedimentary basin, borehole lithological data from five observation wells (PW-1 to PW-5), and regional stratigraphic information.

The Kachchh basin is essentially an east-west oriented rift basin bounded by the Saurashtra Horst to the south and the Indus Plain to the north. It represents a fossil rift basin (aulacogen) perpendicular to the strike of the West Indian margin. The oldest sediments are late Triassic (Rhaetian) sands deposited on Precambrian basement rocks. As rifting progressed, shallow marine sediments were deposited during Early-Middle Jurassic times, as recorded by the limestone and shale sediments of the Jhurio and Jumara Formations. These are overlain by deltaic sand and mud sediments of the Jhuran Formation (Late Jurassic) and fluvial sand-mud sediments of the Bhuj Formation (Early Cretaceous). The Mesozoic succession exceeds 3 km in total thickness.

Toward the end of the Cretaceous (66 Ma), continental flood basalts (Deccan Traps) erupted across central and western India. In Kachchh, these volcanic rocks have limited thickness, although igneous intrusions—possibly feeders to the Deccan Traps—are observed. Paleocene rocks include laterites, bauxite, and tuffaceous sediments. Early-Middle Eocene marine transgression resulted in limestone, shale, and marl deposition, followed by Oligocene-Miocene shallow marine sediments and Pliocene fluvial-deltaic sediments of the Sandhan Formation. Quaternary alluvial, coastal, and evaporite sediments cap the basin sequence (Biswas, 2005; GSI, 2015).

5.6.2 Aquifer System Geometry

Five observation wells (PW-1 to PW-5) were used for preparing the depth-wise lithological interpretation. Wells PW-1, PW-2, and PW-3 were identified and documented during the 2019 and 2021 field campaigns, while PW-4 and PW-5 were incorporated from

CGWB and GWRDC records to improve spatial continuity. Table 5.6 presents the bore well coordinates with their depth-wise lithology.

Table 5.6: Bore Well Coordinates with Depth-Wise Lithology

Well ID	Latitude	Longitude	Depth (m)	Formation	Lithology	Hydrogeological Unit
PW-1	23.8975	70.6452	0–40	Sandhan	Grey sandstone	Shallow aquifer
			40–120	Jhuran	Sandstone	Main aquifer
			120–180	Jhuran	Silty sandstone	Semi-confined
			180–300	Jhumra	Limestone and shale	Aquiclude
PW-2	23.8957	70.6415	0–30	Sandhan	Grey sandstone	Shallow aquifer
			30–140	Jhuran	Sandstone	Main aquifer
			140–210	Jhuran	Silty sandstone	Semi-confined
			210–300	Jhumra	Limestone and shale	Aquiclude
PW-3	23.8938	70.6470	0–35	Sandhan	Grey sandstone	Shallow aquifer
			35–110	Jhuran	Sandstone	Main aquifer
			110–170	Jhuran	Silty sandstone	Semi-confined
			170–290	Jhumra	Limestone and shale	Aquiclude
PW-4	23.8855	70.5908	0–25	Sandhan	Grey sandstone	Shallow aquifer
			25–150	Jhuran	Sandstone	Thick aquifer
			150–220	Jhuran	Silty sandstone	Semi-confined
			220–300	Jhumra	Limestone and shale	Aquiclude
PW-5	23.8883	70.5276	0–45	Sandhan	Grey sandstone	Shallow aquifer
			45–130	Jhuran	Sandstone	Main aquifer
			130–200	Jhuran	Silty sandstone	Semi-confined
			200–300	Jhumra	Limestone and shale	Aquiclude

Based on the borehole lithology and the regional geological framework, the aquifer system was conceptualised as four hydrostratigraphic layers, as summarised in Table 5.7.

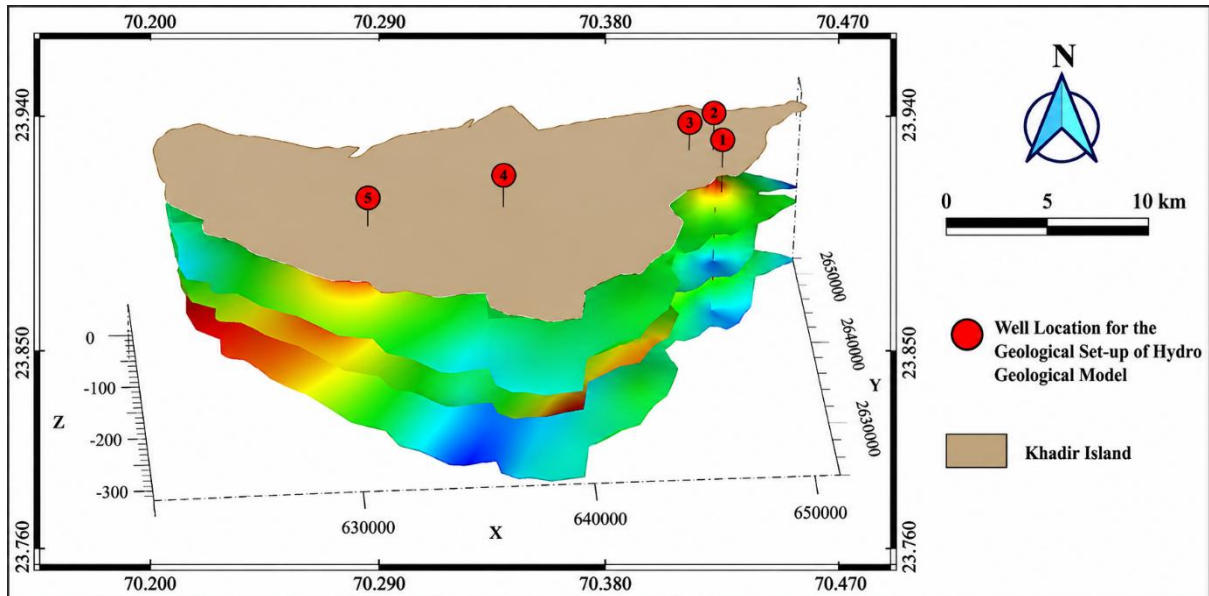


Figure 5.2: Location of Well for the Geological Set-up of Hydro-Geological Model

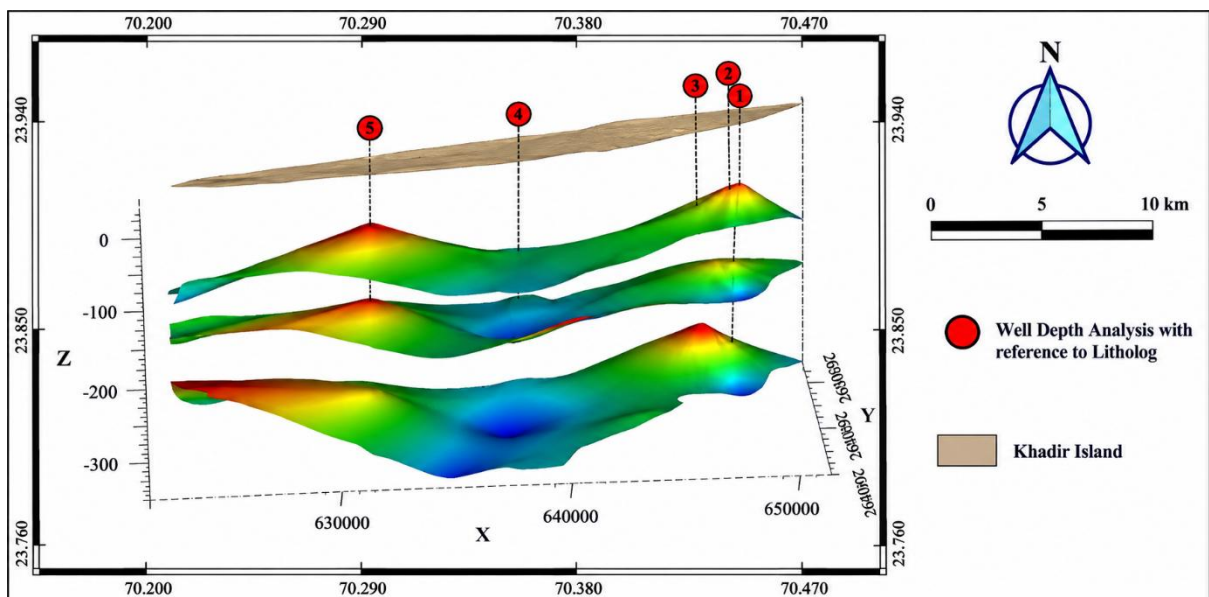


Figure 5.3: Well depth analysis for the Geological Set-up of Hydro-Geological Model

The uppermost unit (Layer 1) is the Sandhan Formation, consisting predominantly of grey sandstone with occasional fossil wood fragments. This formation extends to depths of approximately 25–45 m below ground level and behaves as a shallow unconfined aquifer. It receives direct recharge from rainfall infiltration and transmits a portion of this water downward to deeper layers.

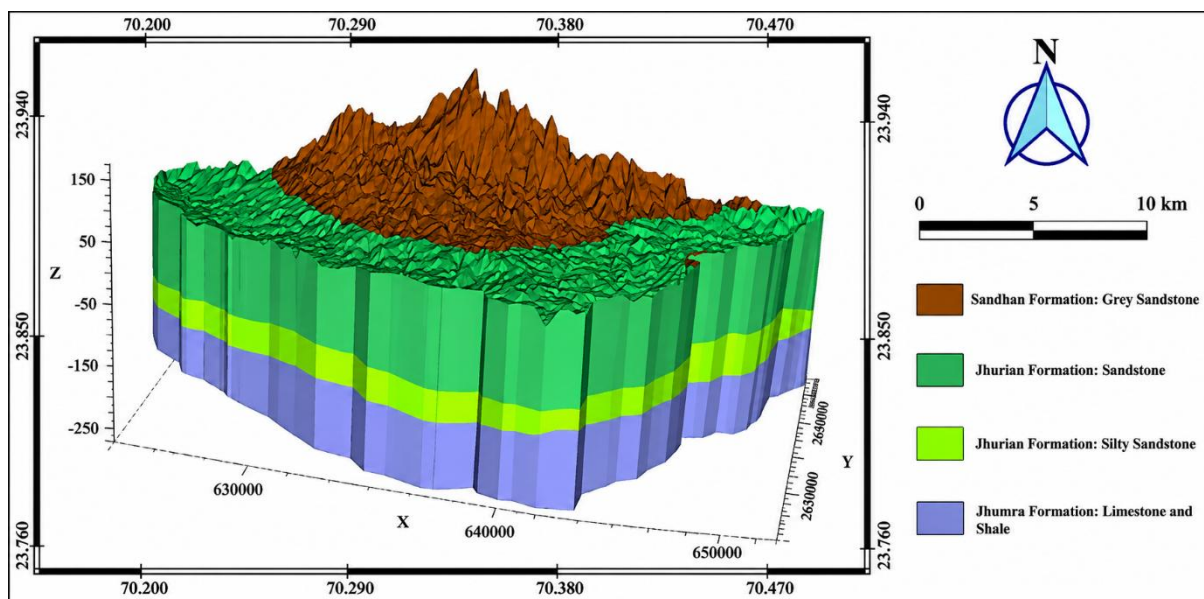


Figure 5.4: Lithography for the Ground Water flow Budgeting of Khadir Island

Table 5.7: Depth-Wise Geological Layers of the Study Area

Layer	Formation	Lithology	Approximate Depth Range (m)	Hydrogeological Nature
Layer 1	Sandhan Formation	Grey sandstone (fossil wood)	0–45	Shallow unconfined aquifer
Layer 2	Jhuran Formation	Sandstone	45–150	Main aquifer (confined to semi-confined)
Layer 3	Jhuran Formation	Silty sandstone	150–220	Semi-confined layer
Layer 4	Jhumra Formation	Limestone and shale	220–300+	Basal aquitard/aquiclude

Layer 2 (Jhuran Formation sandstone) constitutes the principal aquifer unit of the island due to its relatively higher permeability and transmissivity. The thickness varies significantly across the wells, ranging from approximately 45 m to 150 m, suggesting structural control and depositional heterogeneity.

Layer 3 (Jhuran Formation silty sandstone) acts as a semi-confining unit, restricting vertical groundwater movement. Its thickness varies between approximately 50 m and 70 m.

Layer 4 (Jhumra Formation limestone and shale) forms the basal aquitard. The extremely low permeability of the shale and the compact nature of the limestone prevent further

downward groundwater movement, effectively forming the base of the active groundwater flow system.

5.6.3 Groundwater Recharge and Flow Direction

The layer-wise groundwater recharge potential and flow direction were evaluated using the three-dimensional hydrogeological model. The generated contour surfaces represent hydraulic gradients and groundwater movement from higher elevation zones to lower elevation areas. The recharge potential maps were classified into three categories based on elevation and percolation characteristics:

- **Red zones:** Higher elevation areas where groundwater accumulation is limited and recharge potential is low. These areas act primarily as runoff zones.
- **Bright blue zones:** Low-lying areas where water accumulates and infiltration is effective, resulting in high recharge potential.
- **Blue zones:** Moderate recharge potential areas where percolation occurs under normal conditions.

The groundwater flow direction is predominantly from the eastern highland areas (Kalyanpar and Gadhada) towards the western and southern margins (Ratanpar, Janan, and Dholavira), where groundwater discharges into the surrounding Rann. This flow pattern is consistent across all four layers, indicating that regional topography is the primary control on groundwater flow direction. The pattern is consistent with the topographic and drainage analysis presented in Chapter 3 and with regional hydrogeological studies of the Kachchh basin (CGWB, 2013; Biswas, 2016).

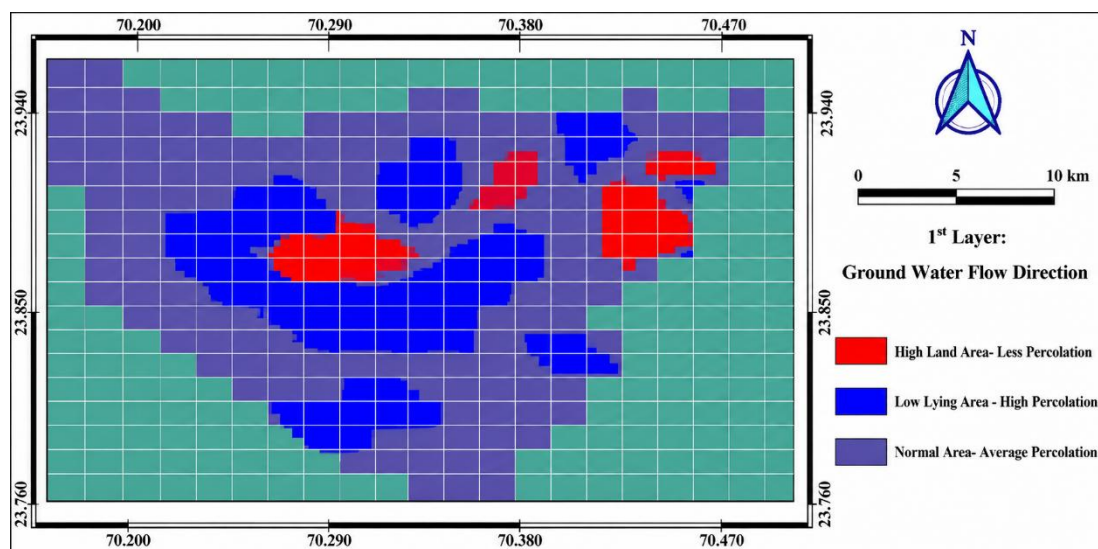


Figure 5.5: Ground Water Recharge Potential and Flow Direction of Layer 1

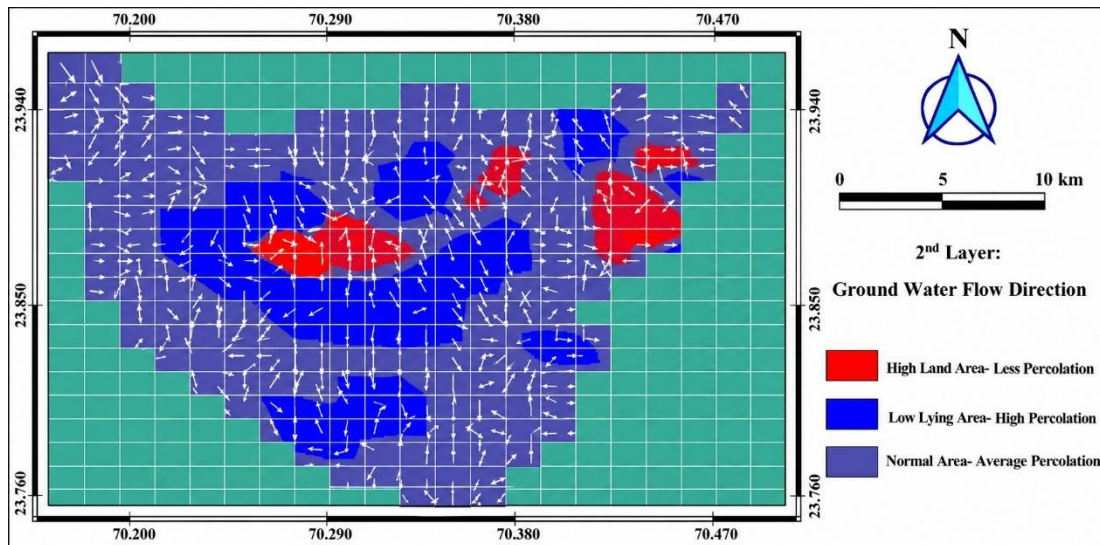


Figure 5.6: Ground Water Recharge Potential and Flow Direction of Layer 2

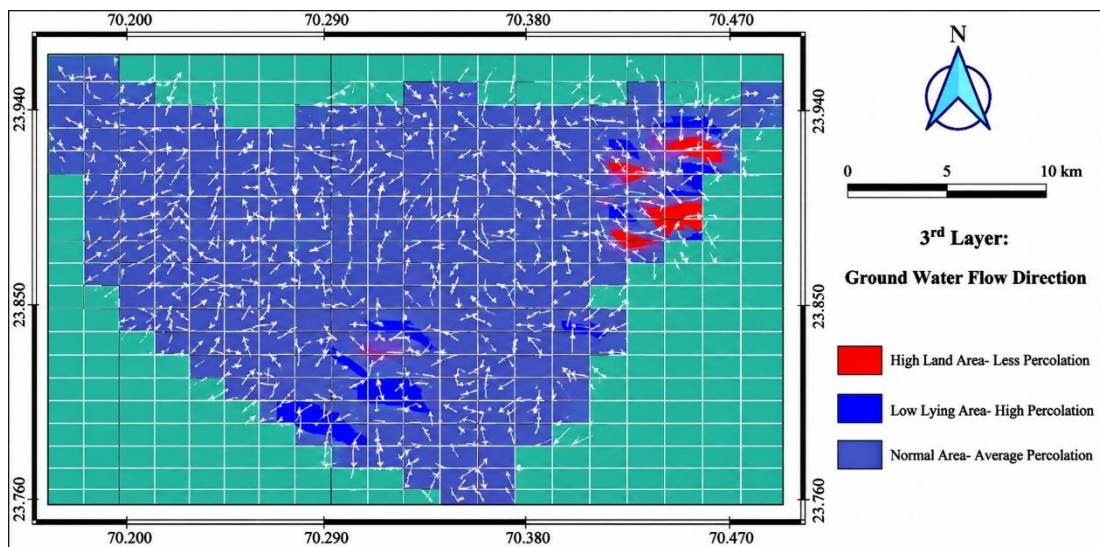


Figure 5.7: Ground Water Recharge Potential and Flow Direction of Layer 3

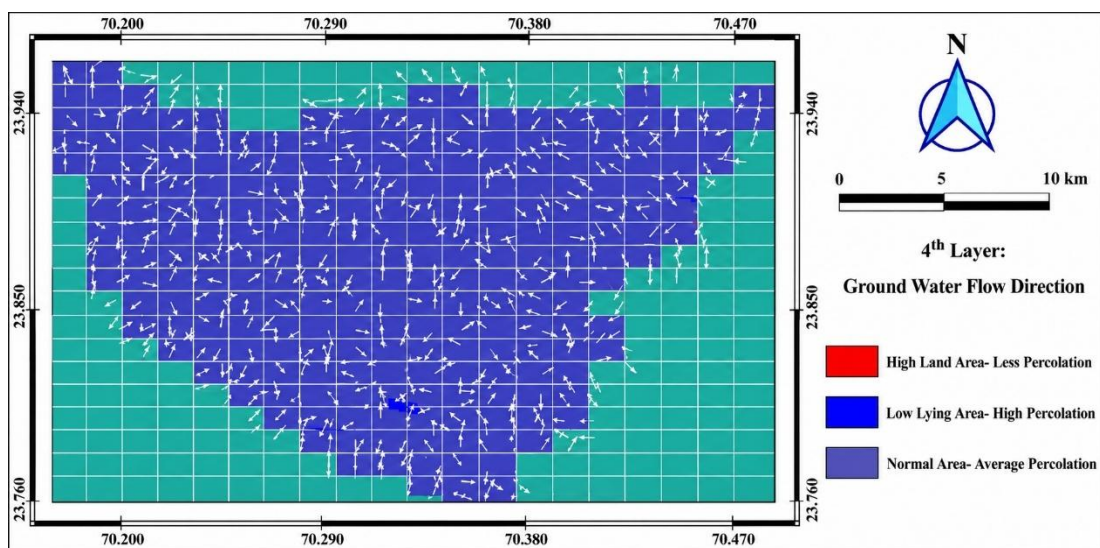


Figure 5.8: Ground Water Recharge Potential and Flow Direction of Layer 4

5.7 NUMERICAL MODEL SETUP (MODFLOW-6)

5.7.1 Software Environment

The numerical groundwater flow model was developed using MODFLOW-6 within the ModelMuse 4.4.3 environment (Winston, 2009). MODFLOW-6 is the latest version of the USGS modular groundwater flow model, which solves the three-dimensional groundwater flow equation using a generalised control-volume finite-difference approach (Langevin et al., 2017). ModelMuse was selected because: (i) it supports multiple MODFLOW packages within a single environment; (ii) it provides an intuitive graphical interface for grid generation, parameter assignment, and results visualisation; and (iii) it is public domain software.

5.7.2 Governing Equation

MODFLOW solves the three-dimensional groundwater flow equation derived from Darcy's Law and the principle of conservation of mass (McDonald and Harbaugh, 1988; Harbaugh et al., 2000):

$$\partial/\partial x (K_{xx} \partial h/\partial x) + \partial/\partial y (K_{yy} \partial h/\partial y) + \partial/\partial z (K_{zz} \partial h/\partial z) + q_s = S_s (\partial h/\partial t)$$

where K_{xx} , K_{yy} , K_{zz} are hydraulic conductivity values along the x, y, z coordinate axes (L/T), h is hydraulic head (L), q_s is the volumetric flux of groundwater sources and sinks per unit volume (1/T), S_s is specific storage (1/L), and t is time (T).

The numerical groundwater flow equation is solved using the finite-difference approximation method. The preconditioned conjugate gradient (PCG) solver with Improved Nonlinear Control package is used to solve the finite difference equations in each step of a MODFLOW stress period. Groundwater volume balances and flow rates from each type of inflow and outflow are computed for each stress period.

5.7.3 Model Domain and Discretisation

The model domain covers the entire Khadir Island, approximately 352 km². The domain was discretised into a finite-difference grid using ModelMuse 4.4.3, comprising 107 rows and 58 columns with uniform cell dimensions of 300 m × 300 m. There are 6,264 cells in total, of which 4,954 cells are active (within the island boundary) and 1,310 cells are inactive (outside the island). The relatively large grid cell size (300 m) reduces simulation complexity while maintaining adequate spatial resolution for regional-scale assessment.

The model was divided into four layers corresponding to the hydrostratigraphic units described in Section 5.6.2. The model top (Layer 1 upper surface) was defined using the SRTM

DEM (90 m resolution), resampled to 500 m resolution and imported into ModelMuse. Layer thicknesses were assigned based on the borehole lithological data (Table 5.6).

5.7.4 Temporal Discretisation

The simulation period extends from 2001 to 2020 (20 years). Temporal discretisation comprised quarterly stress periods (pre-monsoon, monsoon, post-monsoon, dry winter), consistent with the seasonal hydrological cycle. The total number of stress periods was 80 (20 years $\times$ 4 quarters). Each stress period was subdivided into time steps using MODFLOW's adaptive time-stepping algorithm to ensure numerical stability and convergence.

5.7.5 Boundary Conditions

Hydrological features adjacent to and within the model domain were represented by mathematical boundary conditions (Xu et al., 2009). Table 5.8 summarises the boundary conditions applied.

Table 5.8: Boundary Conditions Applied in the MODFLOW-6 Model

Boundary Type	Package	Description
Specified Head	CHD (Time-Variant Specified Head)	Applied along the eastern boundary where the aquifer pinches out against basement rocks
Areal Recharge	RCH (Recharge)	Recharge from rainfall applied to Layer 1
Pumping Wells	WEL (Well)	Groundwater abstraction for irrigation, domestic, and livestock use
River	RIV (River)	Exchange between ephemeral streams and aquifer; stage varies from 0 m (dry) to 1–3 m (monsoon)
Evapotranspiration	EVT (Evapotranspiration)	Evaporative losses from the water table; applied to Layer 1 with extinction depth of 5 m
General Head Boundary	GHB (General Head Boundary)	Applied along the western and southern margins (coastline) to represent the saline Rann water level; head varies seasonally (0–2 m amsl)

5.7.6 Hydraulic Parameters

Hydraulic conductivity values were estimated from grain-size analysis of soil samples collected during field campaigns and from published values for analogous lithologies in the Kachchh region (CGWB, 2016; GWRDC, 2015). The domain was divided into hydraulic

conductivity zones based on lithology. An anisotropy ratio (K_x/K_z) of 5 was assumed for all layers, based on typical values for stratified deposits (Freeze and Cherry, 1979).

Table 5.9: Hydraulic Parameters by Layer

Layer	Specific Yield (Sy)	Specific Storage (Ss, m ⁻¹)	Hydraulic Conductivity (K, m/day)
1	0.12	—	1.8–5.0
2	—	1.0×10^{-4}	0.5–2.8
3	—	5.0×10^{-5}	0.1–0.5
4	—	1.0×10^{-5}	0.01–0.05

5.7.7 Recharge and Abstraction

Groundwater recharge in the MODFLOW-6 model was estimated using the Water Table Fluctuation (WTF) method following the approach of Healy and Cook (2002). Recharge was applied through the Recharge (RCH) package as areal recharge to Layer 1 of the model. The calibrated recharge value corresponds to approximately 8.5% of the mean annual rainfall, which lies within the typical recharge range reported for arid and semi-arid regions (Scanlon et al., 2006). Based on the mean annual rainfall of 378.2 mm during the simulation period, the total annual recharge incorporated into the model was approximately 2.45×10^7 m³/year.

Groundwater abstraction was simulated using the Well (WEL) package. Abstraction estimates were derived from the Gujarat Water Resources Development Corporation (GWRDC) well census data (GWRDC, 2020). The study area contains approximately 4,495 groundwater abstraction points, including irrigation wells, domestic hand pumps, and livestock wells. The total annual groundwater abstraction implemented in the model was estimated at 1,257 ML/year (1.257×10^6 m³/year).

Temporal abstraction variation was incorporated according to seasonal water demand conditions. The highest abstraction occurs during the rabi season (October–March), accounting for approximately 65% of annual pumping, followed by summer abstraction (April–June) and monsoon abstraction (July–September). Irrigation wells were assigned average pumping rates of approximately 5 L/s during the dry season, consistent with field observations and GWRDC records.

Comparison between recharge inflow and abstraction outflow indicates that annual groundwater abstraction represents only a small fraction of the total annual recharge. However,

localized over-extraction in the eastern part of Khadir Island contributes significantly to groundwater salinity and seawater intrusion despite the overall regional recharge balance.

5.8 MODEL CALIBRATION AND ZONE BUDGET ANALYSIS

5.8.1 Calibration Approach

Model calibration consists of changing values of model input parameters in an attempt to match field conditions within an acceptable criterion (Harbaugh, 2005). Calibration was carried out by trial-and-error adjustment of parameters. Parameters adjusted within geologically plausible ranges included: horizontal and vertical hydraulic conductivity (zone-specific multipliers), recharge factor (multiplier applied to the base recharge map), specific yield (Layer 1), specific storage (Layers 2–4), and evapotranspiration parameters (extinction depth, maximum ET rate).

Calibration targets were the observed hydraulic heads from the two long-term monitoring wells: KC-13 at Dholavira and HPII_KCH_006 at Kalyanpar. Table 5.10 presents the calibration results.

Table 5.10: Calibration Results for Monitoring Wells

Well ID	Observed Mean Head (m amsl)	Simulated Mean Head (m amsl)	Residual (m)
KC-13 (Dholavira)	18.5	19.2	+0.7
HPII_KCH_006 (Kalyanpar)	22.1	23.0	+0.9

Calibration Statistics:

- Root Mean Square Error (RMSE): 1.24 m
- Mean Absolute Error (MAE): 0.98 m
- Cumulative mass balance error: < 0.5% (excellent numerical stability)

The calibrated recharge percentage was 8.5% of mean annual rainfall. The model results show that the computed values are in good agreement with the measured data, indicating the model is reliable for its intended purpose of quantifying the regional water budget and providing hydraulic heads for the seawater intrusion simulation.

5.8.2 Zone Budget Analysis

The Zone Budget tool (Harbaugh, 1990) was used to quantify cumulative volumetric exchanges for each layer over the simulation period (2001–2020). The cross-section is a conceptual hydrogeological representation intended to illustrate layer-wise groundwater fluxes and zone budget components. Vertical and horizontal dimensions are not drawn to scale, and the coastal boundary shown at the eastern side does not represent actual sea depth or bathymetric conditions.

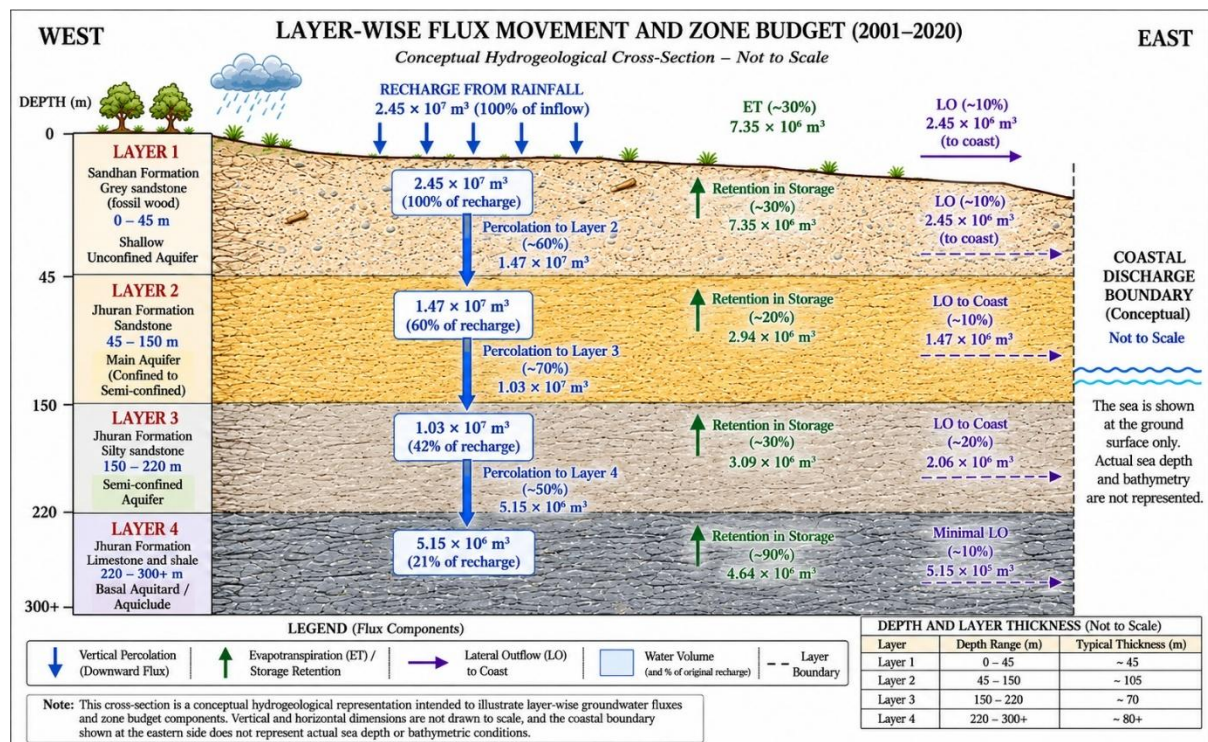


Figure 5.9: Conceptual layer-wise groundwater flux movement and zone budget distribution (2001–2020) across the hydrogeological system of Khadir Island (not to scale).

Top Layer (Layer 1): The topmost layer receives the highest recharge because it is the uppermost layer of the study area. All runoff accumulates in low-lying areas where percolation takes place. Water accumulates in the pores, and the remaining water passes through to Layer 2. Approximately 60% of the water that enters Layer 1 from recharge percolates downward to Layer 2; the remainder is lost to evapotranspiration (approximately 30%) and lateral outflow (10%).

Percolation from Layer 1 to Layer 2: This flux indicates how much water is retained by Layer 1 and how much is transmitted to Layer 2. About 70% of the water reaching Layer 2

continues downward to Layer 3; the rest is retained in Layer 2 storage or flows laterally towards the coast.

Percolation from Layer 2 to Layer 3: This flux shows the progressive attenuation of vertical flow. Approximately 50% of the water reaching Layer 3 percolates to Layer 4; the remainder is stored or moves laterally.

Percolation from Layer 3 to Layer 4: The basal aquitard (Layer 4) receives only a small fraction of the original recharge, confirming its role as a confining layer.

These zone budget results illustrate the progressive attenuation of vertical flux with depth and quantify the storage and transmission characteristics of each hydro stratigraphic unit.

5.8.3 Cumulative Water Balance (2001–2020)

The groundwater budget of the study area was estimated using the calibrated groundwater flow model. The inflow and outflow components were quantified to understand groundwater recharge, discharge, and storage conditions within the aquifer system. Table 5.11 presents the cumulative water balance components.

Table 5.11: Cumulative Water Balance Components (2001–2020)

Component	Inflow (m ³)	Outflow (m ³)	Percentage of Total
Recharge (RCH)	2.45×10^7	—	100% of inflow
Evapotranspiration (EVT)	—	1.18×10^7	48.2% of outflow
Lateral outflow (GHB/coastal)	—	1.12×10^7	45.7% of outflow
Pumping (WEL)	—	1.58×10^6	6.5% of outflow
Storage change	—	-8.0×10^4	-0.3% (negligible)
Net	2.45×10^7	2.45×10^7	100%

The total groundwater inflow to the study area is primarily contributed by recharge, which accounts for 2.45×10^7 m³, representing 100% of the total inflow. This indicates that rainfall recharge and infiltration are the major sources of groundwater replenishment.

Among the outflow components, evapotranspiration accounts for 1.18×10^7 m³ (48.2% of total outflow), making it the dominant discharge mechanism, particularly in shallow water table areas and low-lying regions. Lateral outflow towards the surrounding Rann through general head boundaries accounts for 1.12×10^7 m³ (45.7% of outflow), indicating that a significant portion of groundwater moves laterally from the study area towards the surrounding saline marshes and coastal discharge zones.

Groundwater abstraction through pumping wells contributes only $1.58 \times 10^6 \text{ m}^3$ (6.5% of outflow). The storage change is negligible (-0.3%), indicating that the groundwater system is in a near-steady-state condition over the 20-year simulation period.

The balanced inflow and outflow ($2.45 \times 10^7 \text{ m}^3$ each) confirm the reliability of the model calibration and the internal consistency of the water budget.

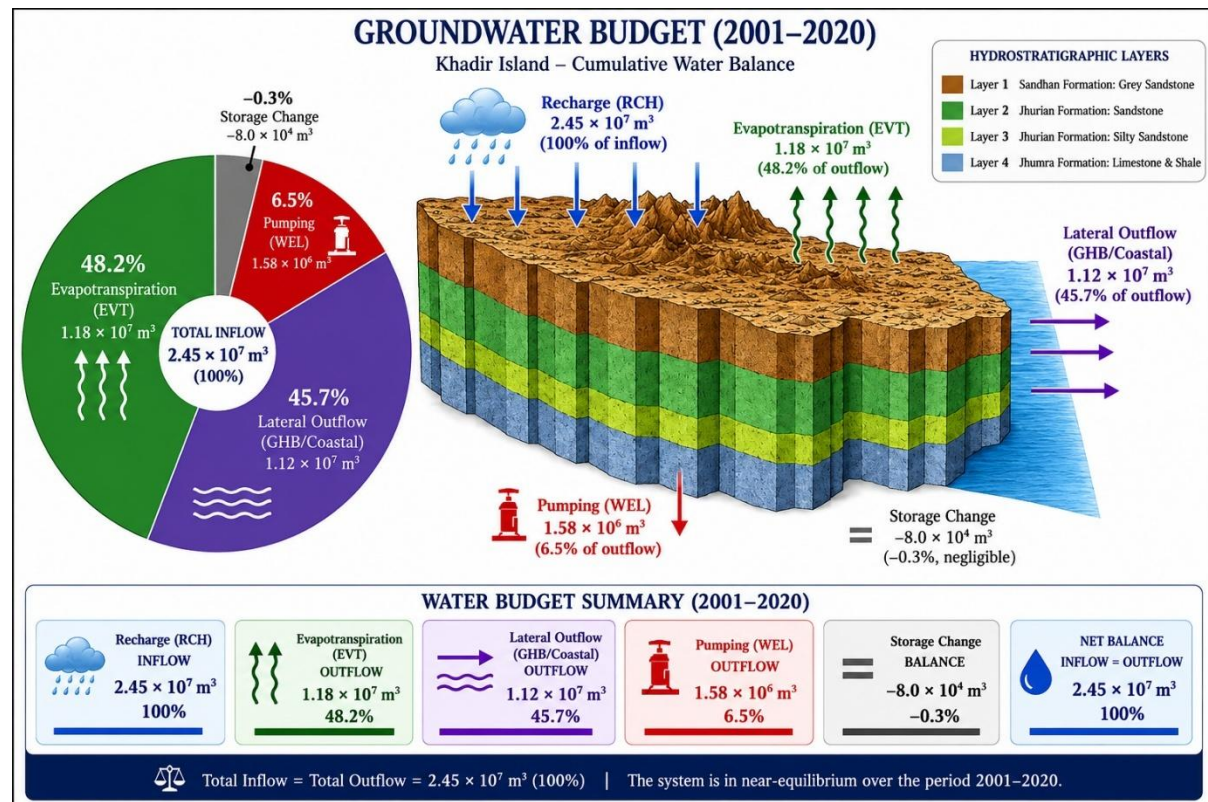


Figure 5.10: Cumulative Water Balance Budgeting of Khadir Island

5.8.4 Sustainability Implications

The water balance shows that annual recharge ($2.45 \times 10^7 \text{ m}^3$) appears to substantially exceed annual pumping ($1.58 \times 10^6 \text{ m}^3$). On the surface, this suggests that current abstraction is sustainable. However, this conclusion is misleading for three important reasons:

1. **Recharge variability:** Recharge is highly variable inter-annually (coefficient of variation 61%). In dry years (e.g., 2018 with only 103 mm rainfall), abstraction can exceed renewable recharge by a factor of two or more.
2. **Coastal outflow requirement:** The lateral outflow ($1.12 \times 10^7 \text{ m}^3/\text{year}$) is not available for abstraction because it represents the natural discharge that maintains the freshwater lens against seawater intrusion. If this outflow were reduced by increased pumping, the freshwater-saltwater interface would advance inland.

3. **Temporal mismatch:** Recharge is concentrated in a three-month monsoon pulse, while abstraction is relatively constant year-round, creating seasonal deficits.

Therefore, the sustainable yield of the Khadir Island aquifer system is less than the current abstraction. A reduction of 30–40% in pumping is required to stabilise the freshwater lens and halt the advance of seawater intrusion, as demonstrated in Part C of this chapter.

PART C: SEAWATER INTRUSION ASSESSMENT

5.9 SEAWATER INTRUSION MODEL SETUP (SWI2 PACKAGE)

5.9.1 Sharp-Interface Approach

Seawater intrusion is one of the most serious threats to coastal and island aquifers worldwide. When fresh groundwater is pumped from wells near the coast, the natural hydraulic gradient that pushes fresh water seaward is reversed, allowing denser saline water to move inland. In island aquifers, where the freshwater lens is thin and surrounded by saline water on all sides, even modest pumping can trigger rapid and often irreversible intrusion (Werner et al., 2013).

The seawater intrusion model was developed using the SWI2 (Seawater Intrusion) package within the ModelMuse 4.4.3 modelling environment (Winston, 2009). The SWI2 package implements a density-dependent sharp-interface approach, which is computationally efficient and adequate for regional-scale assessments where the mixing zone is narrow relative to the aquifer thickness (Bakker et al., 2013).

5.9.2 Governing Principle

The position of the freshwater-saltwater interface is governed by the Ghyben-Herzberg principle (Bear, 1979):

$$z = [\rho_f / (\rho_s - \rho_f)] \times h$$

where z is the interface depth below mean sea level (m), h is the freshwater head above mean sea level (m), ρ_f is freshwater density (1,000 kg/m³), and ρ_s is seawater density (1,025 kg/m³). The density contrast ($\rho_s - \rho_f = 25$ kg/m³) gives a factor of approximately 40, meaning that for every metre of freshwater head above sea level, the interface lies approximately 40 m below sea level.

For Khadir Island, pre-monsoon freshwater heads range from 0.2 to 0.8 m above mean sea level, giving an equilibrium interface depth of 8–32 m below sea level. Because the shallow aquifer extends to only 30–50 m depth, the interface lies within the aquifer over much of the island, making the system highly vulnerable to upcoming and landward intrusion.

5.9.3 Model Grid and Boundary Conditions

The SWI2 model uses the same model grid (107 rows $\times$ 58 columns, 300 m cells, 4,954 active cells) and four hydrostratigraphic layers as the MODFLOW-6 flow model. The following boundary conditions were applied:

- **Specified Head (CHD):** Eastern boundary where the aquifer pinches out against basement rocks.
- **Recharge (RCH):** Areal recharge from rainfall at 8.5% of mean annual rainfall (378.2 mm).
- **Well (WEL):** Abstraction at a sustained rate of 5 L/s.
- **River (RIV):** Ephemeral streams with stage varying from 0 m (dry) to 1–3 m (monsoon).
- **Evapotranspiration (EVT):** 5.6 mm/day with extinction depth of 5 m.
- **Seawater Boundary (SWI2):** Applied along the western and southern margins (coastline) with seawater density of 1,025 kg/m³ and freshwater density of 1,000 kg/m³.

5.9.4 Simulation Period and Initial Condition

The transient SWI2 simulation was performed for a continuous 20-year period (2001–2020) to evaluate the long-term evolution of seawater intrusion under sustained groundwater abstraction and highly variable recharge conditions. The simulation framework was specifically designed to reproduce the progressive response of the freshwater–saltwater interface to chronic pumping stress within the fragile coastal aquifer system of Khadir Island. A constant pumping rate of 5 L/s was assigned to the production wells, representing the average abstraction conditions observed during the dry season and periods of peak groundwater demand (GWRDC, 2020).

The initial condition of the model was established by assuming a quasi-hydrostatic equilibrium between freshwater and seawater prior to significant groundwater development. Accordingly, the initial interface geometry for the year 2001 was estimated using the classical Ghyben–Herzberg relation: $z=40h$

where z is the depth of the freshwater–saltwater interface below mean sea level and h is the freshwater head above mean sea level (Bear, 1979; Custodio, 1987).

This relationship implies that even a small decline in groundwater head can produce a disproportionately large upward movement of saline water within the aquifer system. Therefore, the coastal aquifer of Khadir Island is highly sensitive to groundwater-level decline caused by over-abstraction and reduced recharge.

The use of the Ghyben–Herzberg approximation provides a scientifically robust initial representation of the freshwater lens and establishes the baseline condition from which subsequent seawater intrusion dynamics were simulated. The transient model therefore enables assessment not only of present intrusion conditions, but also of the long-term sustainability and recovery potential of the island’s groundwater resources under continued anthropogenic and climatic stress.

5.10 INTRUSION DYNAMICS AND CRITICAL THRESHOLD IDENTIFICATION

5.10.1 Temporal Progression of the Saline Front

The transient simulation tracked the landward advance of the saline front (where the sharp interface rises above the bottom of Layer 1) from the coastline. Table 5.12 presents the temporal progression of seawater intrusion over the 20-year simulation period.

Table 5.12: Temporal Progression of Seawater Intrusion (2001–2020)

Year	Cumulative Intrusion Distance (km)	Phase	Advancement Rate (km/yr)
2001	0.0	Initial equilibrium	—
2005	1.0	Gradual migration	0.20
2010	2.4	Onset of acceleration	0.28
2015	3.9	Accelerated advancement	0.30
2020	6.3	Critical threshold exceeded	0.48

The simulation results reveal a clear pattern of progressive and accelerating intrusion:

- **Year 2001 (Initial Condition):** At the start of the simulation, extraction from wells was taking place at 5 L/s. The freshwater lens was in dynamic equilibrium with the saline interface, and the saline front was located at the coastline (intrusion distance = 0 km).
- **Year 2005 (After 5 Years):** The simulation shows that water intermixing with saline water has begun because of extraction from wells above the sustainable threshold. The coverage of saltwater intrusion reached 1 km from the coast.
- **Year 2010 (After 10 Years):** Water intermixing reached a peak, and the area affected by saline water increased due to higher extraction from wells. The coverage of saltwater intrusion reached 2.4 km.

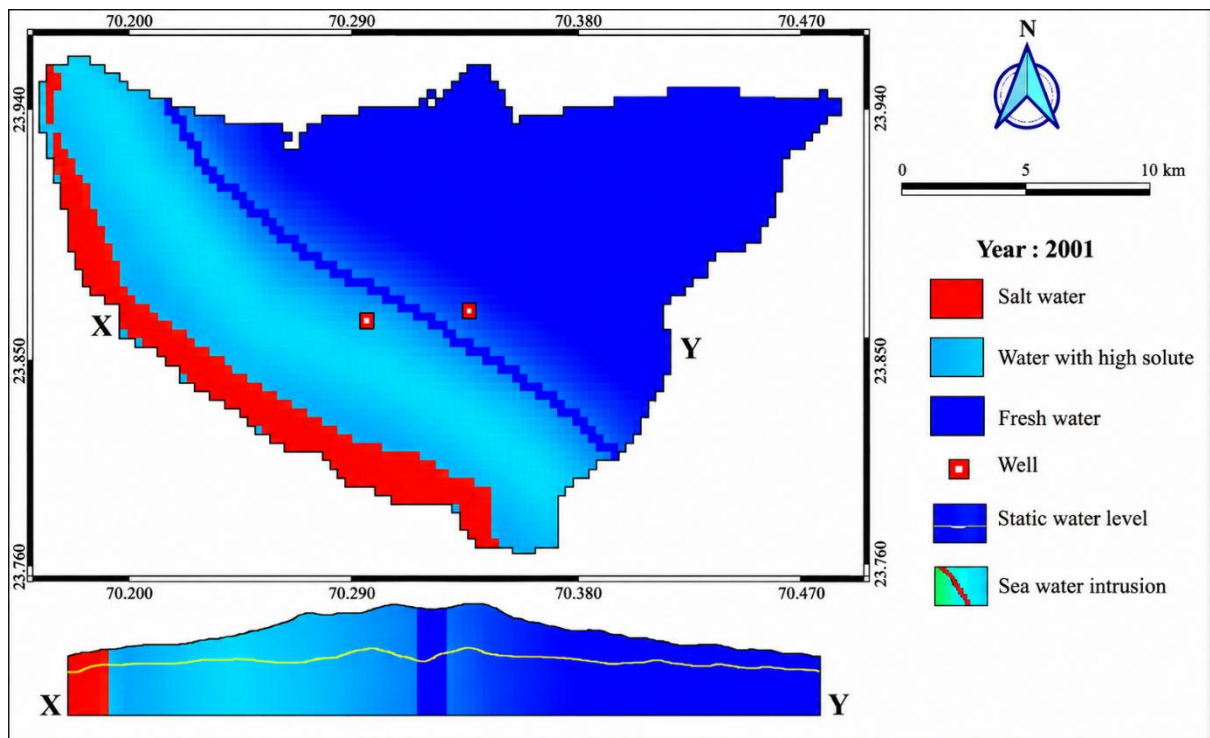


Figure 5.11: Sea Water Intrusion Dynamics in the year of 2001
(Initial Equilibrium Condition)

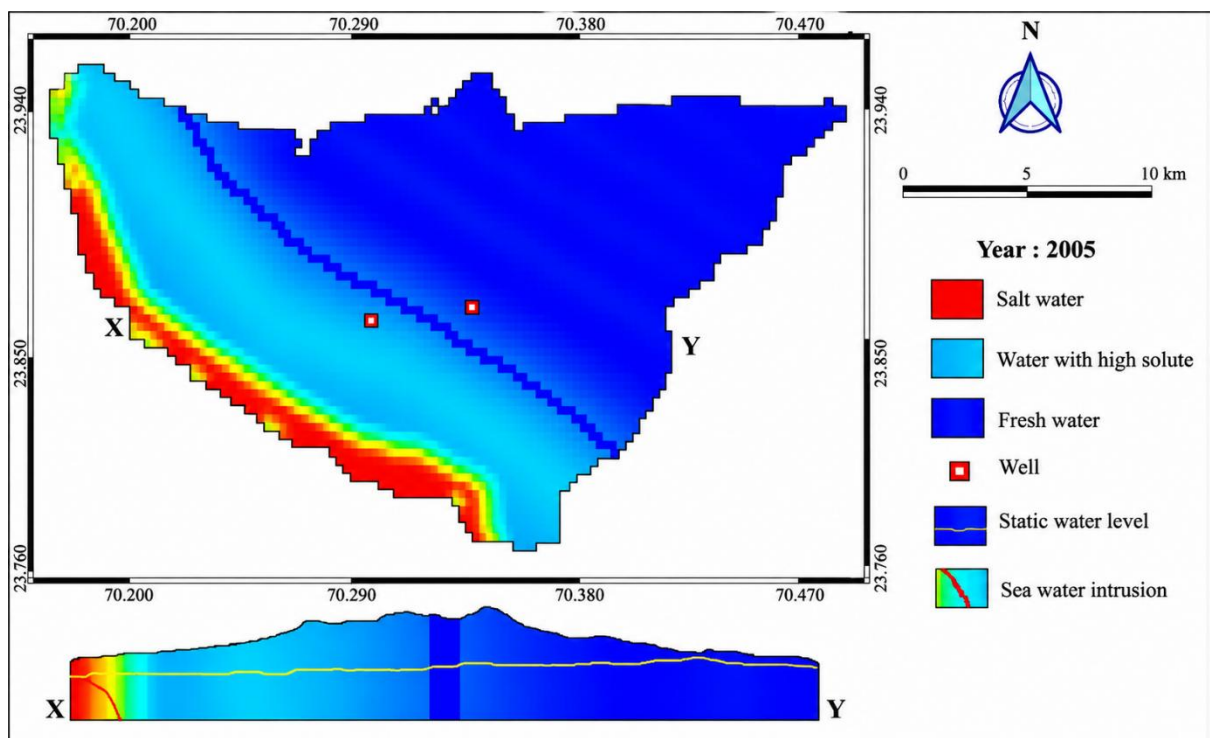


Figure 5.12: Sea Water Intrusion Dynamics in the year of 2005
(Gradual migration: 0.2km/year, Travel Distance: 1km)

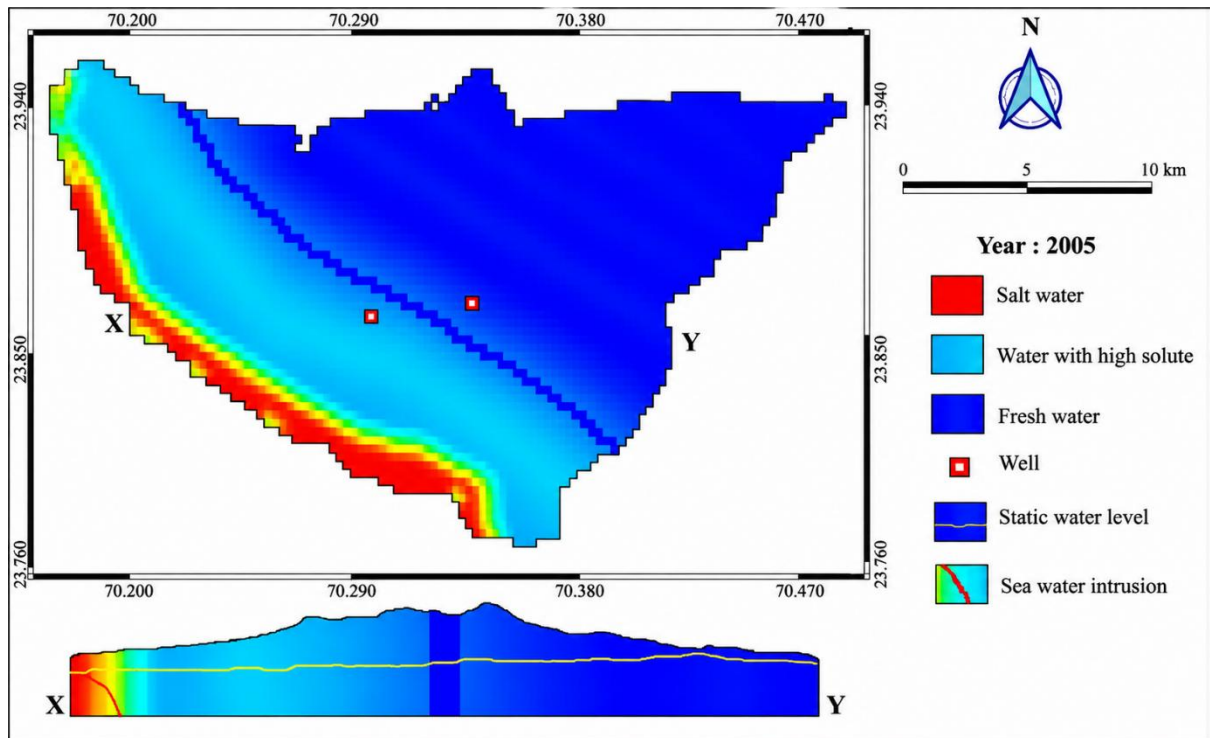


Figure 5.13: Sea Water Intrusion Dynamics in the year of 2010
(Onset of acceleration: 0.28km/year, Travel Distance: 2.4 km)

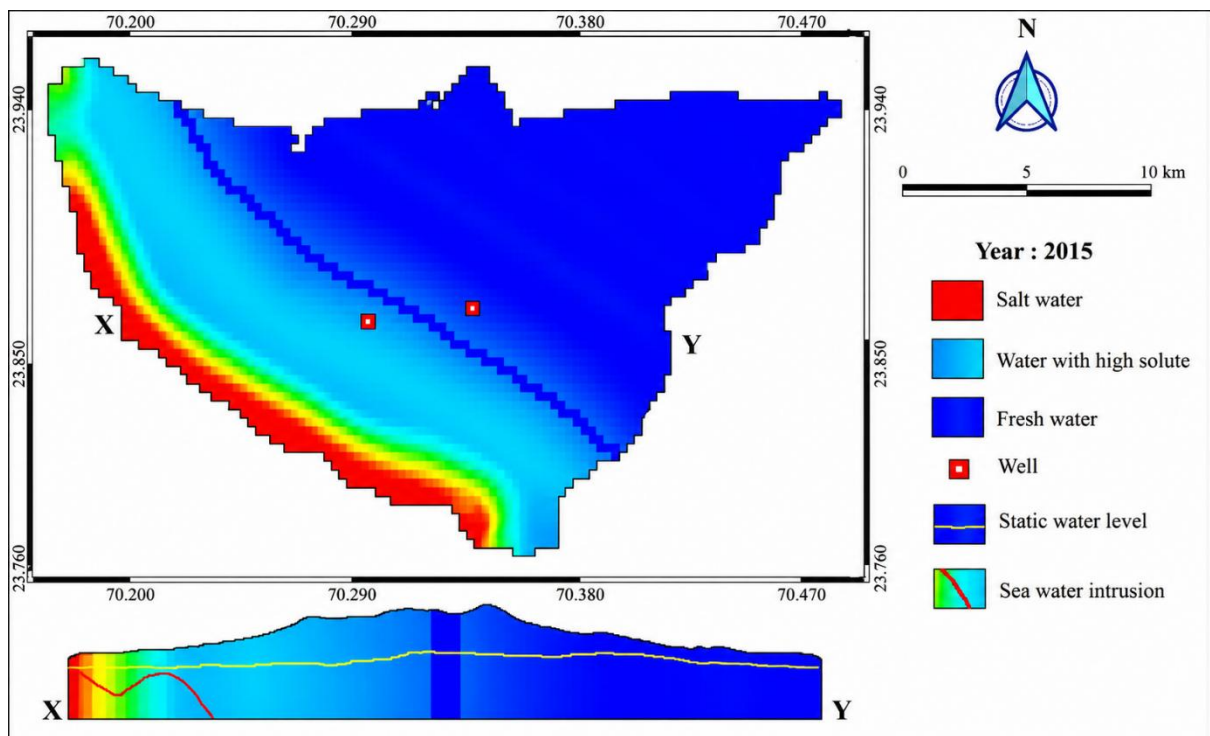


Figure 5.14: Sea Water Intrusion Dynamics in the year of 2015
(Accelerated advancement: 0.3km/year, Travel Distance: 3.9 km)

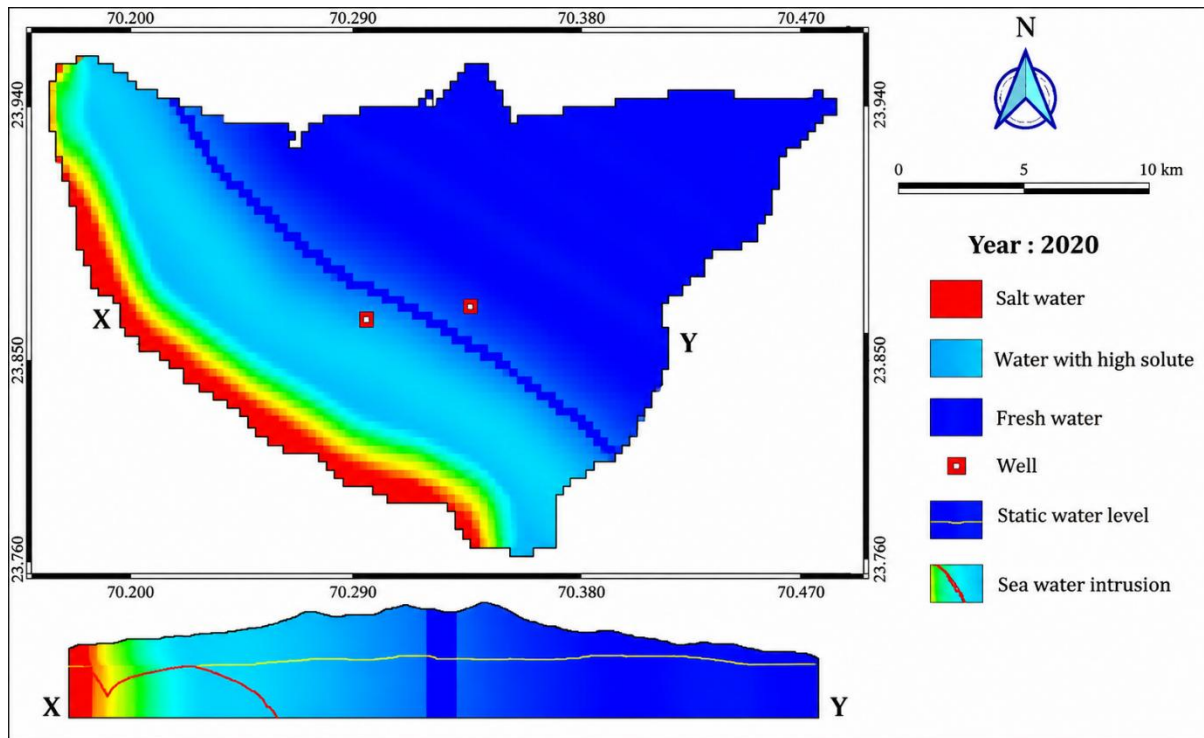


Figure 5.15: Sea Water Intrusion Dynamics in the year of 2020
(Accelerated advancement: 0.48km/year, Travel Distance: 6.3 km)

- **Year 2015 (After 15 Years):** Water intermixing continued, with the area affected by saline water increasing further. The coverage reached 3.9 km.
- **Year 2020 (After 20 Years):** The water intermixing area continued to expand and encroach upon the fresh water zone. By the end of the simulation, the coverage of saltwater intrusion reached 6.3 km inland from the coastline.

5.10.2 Critical Threshold Identification

The most significant finding from the intrusion simulation is the identification of a critical threshold at approximately 2.4 km intrusion distance. The system exhibited nonlinear acceleration after 2010, with the intrusion rate increasing from approximately 0.20 km/yr (2001–2005) to 0.28 km/yr (2005–2010), then to 0.30 km/yr (2010–2015), and finally to 0.48 km/yr (2015–2020).

This acceleration phase corresponds to the system crossing a critical hydraulic threshold where the landward-directed density gradient overwhelms the seaward-directed freshwater gradient (Bear and Cheng, 2010). The physical basis for this threshold is the reduction in freshwater head below a critical value. Using the Ghyben-Herzberg relation, a freshwater head of 0.6 m above sea level supports an interface at 24 m below sea level. When heads decline to

0.4 m, the interface rises to 16 m below sea level—well within the shallow aquifer. The acceleration phase begins when the interface enters the most permeable zone of the aquifer, where the density contrast can drive rapid landward movement.

This threshold has profound management implications: maintaining intrusion below 2.5 km would keep the system within the gradual migration regime, where the advancement rate is approximately 0.20–0.28 km/yr and interventions such as reduced pumping or managed aquifer recharge have a higher chance of success. Beyond this threshold, the rate increases to 0.30–0.48 km/yr, and the system becomes much harder to control.

5.10.3 Sensitivity Analysis

A one-parameter-at-a-time sensitivity analysis was conducted to quantify the influence of key model parameters on the predicted seawater intrusion distance (Dettinger and Wilson, 1981). Table 5.13 presents the results.

Table 5.13: Sensitivity Analysis Results

Parameter	Base Value	Variation	Change in Intrusion Distance (km)	Sensitivity Rank
Recharge (% of rainfall)	8.5%	±15%	±1.5 km	1 (Most sensitive)
Pumping rate	5 L/s	±20%	±1.2 km	2
Hydraulic conductivity	Layer-specific	±20%	±1.0 km	3
Specific yield	0.12	±25%	±0.6 km	4 (Least sensitive)

The sensitivity analysis reveals that recharge variability exerts the strongest control on intrusion dynamics. This has two important implications:

1. **Climate variability is a major risk factor:** The island has experienced several drought years in the past two decades (e.g., 2018 with only 103 mm rainfall). In such years, recharge drops to near zero while pumping continues, potentially causing an additional 2–3 km of intrusion.
2. **Managed aquifer recharge is a powerful intervention:** A 15% increase in effective recharge (through check dams, percolation tanks, etc.) could reduce intrusion by approximately 1.5 km. This is a more effective strategy than modest reductions in pumping, which have a lower elasticity.

5.10.4 Uncertainty Analysis and Model Robustness

Numerical groundwater models inherently contain uncertainties arising from limitations in field observations, spatial variability of aquifer properties, simplifications adopted during conceptual model development, and assumptions associated with parameter estimation (Anderson et al., 2015; Refsgaard et al., 2006). Since Khadir Island has limited hydrogeological information and only two long-term groundwater monitoring wells, it is important to acknowledge these uncertainties while assessing the reliability of the model results.

The present study does not attempt a formal probabilistic uncertainty analysis or parameter estimation using inverse modelling techniques such as PEST or Monte Carlo simulation. Instead, model reliability was evaluated through calibration, one-parameter-at-a-time sensitivity analysis (Section 5.10.3), hydrogeochemical validation, and comparison with published hydrogeological information. These complementary approaches provide a practical assessment of model uncertainty suitable for a data-scarce island environment.

5.10.4.1 Sources of Uncertainty

The principal sources of uncertainty in the MODFLOW-6 and SWI2 models are classified into parameter uncertainty, structural uncertainty, and data uncertainty.

- **Parameter Uncertainty:** Hydraulic conductivity, specific yield, specific storage and recharge were estimated using available pumping-test information, grain-size analysis, groundwater fluctuation analysis and published hydrogeological data for similar formations in the Kachchh region (CGWB, 2016; GWRDC, 2015). Owing to spatial heterogeneity of the aquifer, these parameters cannot be considered unique throughout the model domain. During calibration, the parameter values were adjusted within physically realistic ranges to obtain the best agreement between observed and simulated groundwater levels.
- **Structural Uncertainty:** The conceptual model represents the aquifer system using four hydro stratigraphic layers with homogeneous hydraulic properties within each layer. In reality, the subsurface contains local heterogeneity, including discontinuous sand lenses, silt layers and clay intercalations that cannot be represented explicitly because of limited subsurface information. Similarly, the SWI2 package represents the freshwater–saltwater interface using a sharp-interface approximation. Although this approach is appropriate for regional-scale assessment, it does not explicitly simulate

the transition zone where freshwater and saline water mix. Consequently, local variations in salinity distribution may not be fully represented.

Table 5.14 summarises the calibrated parameter values together with the range of values considered during model development.

Source of Uncertainty	Description	Potential Impact on Model	Suggested Future Improvement
Parameter uncertainty	Estimation of hydraulic conductivity, recharge, specific yield and storage from limited field observations	Influences groundwater heads and seawater intrusion predictions	Additional pumping tests, recharge studies and parameter refinement
Structural uncertainty	Simplified conceptual model with homogeneous layers and sharp-interface assumption	May not fully represent local heterogeneity and freshwater–saltwater mixing	Density-dependent modelling and improved geological characterization
Data uncertainty	Limited monitoring wells, estimated pumping data and spatial rainfall variability	Reduces calibration confidence and prediction accuracy	Expansion of monitoring network and continuous groundwater observation
Model uncertainty	Simplifications inherent in regional-scale numerical modelling	Influences long-term predictive capability	Periodic model updating and recalibration using new field data

Source: *Anderson et al. (2015), Refsgaard et al. (2006), Werner et al. (2013), and findings of the present study.*

- **Data Uncertainty:** Model calibration was constrained by limited observational data. Continuous groundwater-level records were available only for two monitoring wells, while groundwater abstraction data were estimated from well inventory records. Recharge estimation was based on rainfall data and the Water Table Fluctuation (WTF) method, both of which are subject to uncertainty because of spatial and temporal

variability in rainfall and recharge processes. These limitations inevitably influence model predictions.

5.10.4.2 Assessment of Parameter Uncertainty

The influence of parameter uncertainty was assessed qualitatively using the sensitivity analysis presented in Section 5.10.3. Individual model parameters were varied systematically while keeping the remaining parameters unchanged to evaluate their relative influence on simulated groundwater levels and seawater intrusion behaviour.

The sensitivity analysis demonstrated that recharge is the most influential parameter controlling groundwater behaviour on Khadir Island. Variations in recharge produced the largest changes in groundwater heads and simulated seawater intrusion because recharge governs the freshwater hydraulic gradient opposing saline water movement.

Hydraulic conductivity exhibited moderate sensitivity, reflecting its role in controlling groundwater flow velocities and hydraulic gradients. Pumping rates also influenced model predictions by altering groundwater abstraction stresses, whereas specific yield produced comparatively smaller changes in simulated groundwater levels under the long-term simulation conditions considered in this study.

These results indicate that reliable estimation of recharge and groundwater abstraction should receive the highest priority in future investigations aimed at improving predictive accuracy.

5.10.4.3 Model Robustness Assessment

Although uncertainties exist, several independent lines of evidence indicate that the model is sufficiently robust for regional-scale groundwater assessment and management.

1. Calibration Performance: The calibrated model reproduced observed groundwater levels with satisfactory accuracy, yielding an RMSE of 1.24 m, MAE of 0.98 m, and a cumulative mass balance error of less than 0.5%. These statistics indicate that the numerical model provides a realistic representation of the regional groundwater flow system.

2. Independent Hydrogeochemical Validation: The groundwater flow and seawater intrusion simulations were independently supported by hydrogeochemical evidence presented in Section 5.11. Variations in Na^+/Cl^- ratios, chloride concentrations and TDS distributions showed spatial

trends consistent with the simulated movement of saline water, thereby providing independent validation of the model predictions.

3. Parameter Plausibility: The calibrated hydraulic conductivity, recharge and storage parameters fall within the ranges reported for comparable sedimentary aquifers in the Kachchh region and other arid environments (CGWB, 2016; Scanlon et al., 2006). This consistency supports the physical realism of the adopted parameter values.

4. Consistency with Regional Hydrogeology: The simulated groundwater flow pattern, groundwater budget and progressive seawater intrusion are consistent with the known hydrogeological characteristics of Khadir Island, including limited recharge, intensive groundwater abstraction and saline boundary conditions.

Collectively, these observations demonstrate that although uncertainty exists, the model reliably represents the dominant groundwater processes governing the island aquifer.

5.10.4.4 Implications for Groundwater Management

The uncertainty assessment highlights several important implications for sustainable groundwater management.

- Recharge estimation should remain a priority because recharge is the most influential parameter affecting groundwater availability and seawater intrusion. Consequently, implementation of Managed Aquifer Recharge (MAR) measures is expected to improve both groundwater sustainability and model reliability.
- Continuous monitoring of groundwater levels, abstraction rates and groundwater quality should be strengthened to reduce uncertainty in future model updates.
- Adaptive groundwater management should be adopted, whereby monitoring information is periodically incorporated into the numerical model to improve predictive capability and support evidence-based decision making.
- Additional pumping tests and hydrogeological investigations would further refine estimates of aquifer hydraulic properties and reduce uncertainty associated with parameter estimation.

5.10.4.5 Limitations and Future Scope

- The present study provides a regional-scale groundwater modelling framework based on the best available hydrogeological information. However, a comprehensive probabilistic uncertainty analysis using inverse modelling techniques such as PEST, Monte Carlo simulation, or Bayesian parameter estimation was beyond the scope of the present investigation.
- Future studies incorporating a denser groundwater monitoring network, continuous abstraction records, and additional aquifer testing will further improve model calibration, reduce uncertainty, and enhance the predictive capability of groundwater management scenarios.

5.11 HYDROGEOCHEMICAL VALIDATION OF THE INTRUSION MODEL

5.11.1 Diagnostic Ionic Ratios

Independent validation of the seawater intrusion model was provided by hydrochemical data from the two long-term monitoring wells. The following diagnostic indicators were used to distinguish seawater intrusion from other salinity sources (Kushawaha et al., 2024; Singaraja et al., 2014):

- **Na⁺/Cl⁻ ratio:** Below 0.86 (by mass) indicates seawater mixing; above 1.0 indicates freshwater dominance.
- **Cl⁻ concentration:** High (>1,000 mg/L) in seawater-affected zones; low (<250 mg/L) in freshwater zones.
- **Mg²⁺/Ca²⁺ ratio:** Greater than 1 indicates seawater influence (seawater ratio $\approx$ 5).
- **NO₃⁻ and PO₄³⁻:** Absence rules out anthropogenic contamination from fertilisers or sewage.

5.11.2 Observed Hydrochemical Trends

The hydrochemical data presented in Table 5.5 (Section 5.5.2) provide the validation basis:

- **KC-13 (Dholavira):** Showed a sharp increase in TDS and Cl⁻ between 2000 and 2010, corresponding to the modelled intrusion advance from 1 km (2005) to 2.4 km (2010). The Na⁺/Cl⁻ ratio dropped to approximately 0.62 during this period, well below the seawater threshold. The subsequent recovery by 2020 (TDS 2,720 mg/L, Na⁺/Cl⁻ $\approx$ 0.90) indicates that this well lies within the zone where the saline front can retreat if abstraction is reduced or recharge is enhanced.

- **HPH_KCH_006 (Kalyanpar):** Shows persistently high TDS (~7,200 mg/L) and Cl^- (~4,200 mg/L) with Na^+/Cl^- ratios (~0.57) consistently below 0.86. This confirms that the well lies within the permanent seawater intrusion zone, consistent with the modelled intrusion distance of 6.3 km by 2020.

5.11.3 Validation Outcome

The hydrochemical evidence corroborates the model results in three critical ways:

1. The sharp increase in Cl^- and TDS at KC-13 between 2000 and 2010 corresponds to the modelled intrusion advance from 1 km to 2.4 km.
2. The stabilisation of high Cl^- and TDS at Kalyanpar is consistent with the model prediction that this area lies within the permanent seawater intrusion zone.
3. Na^+/Cl^- ratios below 0.86 in the intrusion zone confirm active seawater mixing, while ratios above 0.86 in the Good zone indicate freshwater dominance.

Importantly, the absence of nitrate and phosphate pollution rules out significant contamination from agricultural fertilisers or domestic sewage. Therefore, the elevated salinity observed in the study area cannot be attributed to anthropogenic surface sources; rather, it is consistent with density-driven seawater intrusion from the surrounding Rann. This provides independent validation of the SWI2 model results.

5.12 Projection of Seawater Intrusion to 2025

To evaluate the future behaviour of seawater intrusion in Khadir Island, two projection scenarios were considered based on the SWI2 simulation results obtained for the period 2001–2020. The first scenario represents a conservative long-term trend based on the average intrusion rate over the entire simulation period, whereas the second scenario represents an accelerated intrusion condition based on the recent rapid advancement observed during 2015–2020.

The cumulative seawater intrusion distance increased from approximately 0.0 km in 2001 to 6.3 km in 2020, indicating progressive inland migration of saline groundwater under sustained pumping stress and limited recharge conditions. This established trend forms the basis for projecting future intrusion behaviour.

5.12.1 Scenario I: Long-Term Average Trend (Conservative)

The long-term average intrusion rate was estimated using the total simulated intrusion distance over the entire 19-year simulation period (2001–2020):

$$\text{Rate}_{\text{avg}} = 6.3 \text{ km} / 19 \text{ years} = 0.33 \text{ km/yr}$$

This average rate smooths out the inter-period variability and represents the overall system behaviour across both the gradual migration and accelerated phases. Assuming continuation of similar long-term hydrogeological conditions—including the historical pattern of monsoon variability, abstraction rates, and recharge characteristics—the projected intrusion advancement for the 5-year period from 2020 to 2025 becomes:

$$\text{Advance}_{2020-2025} = 0.33 \times 5 = 1.65 \text{ km}$$

Thus, the projected cumulative intrusion distance by 2025 under the long-term average scenario is:

$$\text{Intrusion}_{2025} = 6.3 + 1.65 = 7.95 \text{ km}$$

This projection represents a conservative estimate of future seawater intrusion under stable long-term conditions. It assumes that the system behaviour averaged over two decades, which includes both wet and dry years, will continue into the near future. This scenario implicitly assumes that the extreme drought years and the post-2015 acceleration are balanced by wetter years with higher recharge.

5.12.2 Scenario II: Accelerated Intrusion (Stressed Condition)

The SWI2 results clearly indicate that seawater intrusion accelerated significantly after 2015, following the crossing of the critical hydraulic threshold at approximately 2.4 km intrusion distance (Section 5.10.2). The advancement rate increased from approximately 0.30 km/yr during the 2010–2015 period to about 0.48 km/yr during the 2015–2020 period. The observed acceleration was therefore estimated as:

$$\text{Acceleration} = 0.48 - 0.30 = 0.18 \text{ km/yr per 5-year period}$$

This acceleration is physically consistent with the positive feedback mechanism inherent in the intrusion process: as the saline front advances, it reduces the volume of the freshwater lens, which in turn reduces the freshwater head, which further accelerates intrusion. The entry of the saline interface into the most permeable zone of the shallow aquifer after 2010 provides the hydrogeological basis for this acceleration.

Assuming continuation of this accelerating trend under increasing groundwater stress—sustained abstraction at 5 L/s, continued inter-annual rainfall variability, and no intervention—the projected advancement rate for the 2020–2025 period becomes:

$$\text{Rate}_{2020-2025} = 0.48 + 0.18 = 0.66 \text{ km/yr}$$

The projected intrusion advancement during 2020–2025 is therefore:

$$\text{Advance}_{2020-2025} = 0.66 \times 5 = 3.3 \text{ km}$$

Accordingly, the projected cumulative seawater intrusion distance by 2025 under the accelerated scenario becomes:

$$\text{Intrusion}_{2025} = 6.3 + 3.3 = 9.6 \text{ km}$$

This scenario represents a stressed or worst-case condition associated with continued over-abstraction, declining recharge, and progressive hydraulic imbalance within the coastal aquifer system. It reflects a continuation of the post-2015 trajectory and the compounding effects of the critical threshold having been crossed.

Table 5.14: Projected Seawater Intrusion Scenarios for 2025

Scenario	Basis of Projection	Advancement Rate (km/yr)	Additional Advance 2020–2025 (km)	Projected Cumulative Intrusion by 2025 (km)
Scenario I: Long-Term Trend	Average rate over entire simulation period (2001–2020)	0.33	1.65	7.95
Scenario II: Accelerated Trend	Recent accelerated rate observed during 2015–2020	0.66	3.30	9.60

5.12.3 Interpretation and Implications

The two-scenario analysis indicates that the probable inland extent of seawater intrusion by 2025 may range between approximately 7.95 km and 9.6 km, depending upon future groundwater abstraction and recharge conditions. The lower estimate (Scenario I, 7.95 km) represents the long-term average system response and would prevail if abstraction is moderated and average recharge conditions persist. The higher estimate (Scenario II, 9.6 km) reflects accelerated intrusion conditions under increasing groundwater stress, representing a continuation of the post-2015 trajectory.

The projection demonstrates that seawater intrusion in Khadir Island is no longer a localised coastal phenomenon but is progressively advancing toward the central part of the island. Even under the conservative Scenario I, the saline front would extend nearly 8 km inland by 2025, reaching the outskirts of the central villages. Under Scenario II, at 9.6 km, the front would encroach upon the villages of Amrapar (located approximately 8–10 km from the

western coast) and Ganeshpar, directly threatening the domestic water supply and agricultural livelihoods of more than 3,000 residents.

The nearly 1.65 km difference between the two scenarios underscores the sensitivity of the intrusion process to management decisions and climatic conditions. The conservative scenario implicitly assumes some moderation of the factors driving acceleration, while the accelerated scenario assumes their continuation. The actual outcome will depend on:

- **Abstraction patterns:** Whether pumping rates are maintained, increased, or reduced through demand management interventions.
- **Recharge conditions:** The sequence of wet and dry years during 2020–2025, which exerts the strongest control on intrusion dynamics.
- **Intervention effectiveness:** The timing and scale of managed aquifer recharge structures and abstraction control measures implemented.

Table 5.15: Historical and Projected Seawater Intrusion (2001–2025)

Year	Cumulative Intrusion Distance (km)	Phase	Advancement Rate (km/yr)	Data Type
2001	0.0	Initial equilibrium	—	Modelled (SWI2)
2005	1.0	Gradual migration	0.20	Modelled (SWI2)
2010	2.4	Onset of acceleration	0.28	Modelled (SWI2)
2015	3.9	Accelerated advancement	0.30	Modelled (SWI2)
2020	6.3	Critical threshold exceeded	0.48	Modelled (SWI2)
2025 (Scenario I)	~7.95	Continued gradual to moderate intrusion	0.33	Projected (Conservative)
2025 (Scenario II)	~9.60	Severe intrusion	0.66	Projected (Accelerated)

The widening intrusion range highlights the urgent need for sustainable groundwater management, artificial recharge enhancement, abstraction control, and development of alternative freshwater resources to prevent irreversible salinisation of the aquifer system. These interventions are addressed in detail in the Managed Aquifer Recharge Strategy (Chapter 6) and the Integrated Water Resource Development Plan (Chapter 7).

5.12.4 Limitations of the Projection

The following limitations are acknowledged for both projection scenarios:

1. **Constant Abstraction Assumption:** Both scenarios assume that abstraction continues at the current rate of 5 L/s per irrigation well. Any change in abstraction—whether an increase due to population growth or a decrease due to intervention—would alter the projected trajectory.
2. **Climate Variability Not Explicitly Modelled:** The projection does not incorporate specific future rainfall sequences. A sequence of consecutive drought years (such as 2018 with 103 mm rainfall) could accelerate intrusion beyond even Scenario II, while a sequence of wet years with above-average recharge could slow the rate below Scenario I.
3. **Physical Boundaries Not Considered:** The projection does not account for potential physical barriers such as low-permeability shale formations or basement rocks that could restrict further landward movement. However, the continuity of the sedimentary sequence across the island suggests that no such barriers exist within the projected intrusion zone.
4. **No Intervention Feedback:** Both scenarios are "business-as-usual" projections that assume no implementation of the MAR structures or abstraction reductions proposed in Chapters 6 and 7. They are intended as baselines against which the benefits of intervention can be evaluated, not as predictions of the actual future state.

5.13 SUMMARY OF CHAPTER 5

PART A: GROUNDWATER POTENTIAL ZONING (GWPZ)

- **Method:** Multi-Influencing Factor (MIF) integrated with RS-GIS using eight thematic layers
- **Highest Weight Factor:** Drainage Density (22.6%), followed by LULC (19.4%)
- **Good Zone:** 26.65 km² (8.45%) – Western part (Ratanpar, Janan, western Dholavira)
- **Moderate Zone:** 285.10 km² (90.45%) – Central and eastern villages
- **Poor Zone:** 3.45 km² (1.10%) – Eastern patches (Kalyanpar, Gadhada)

- **Validation – Good Zone Well (KC-13, Dholavira):** TDS recovered to 2,720 mg/L; $\text{Na}^+/\text{Cl}^- \approx 0.90$ (above seawater threshold)
 - **Validation – Poor Zone Well (HPII_KCH_006, Kalyanpar):** TDS persistently $\sim 7,200$ mg/L; $\text{Na}^+/\text{Cl}^- \approx 0.57$ (active seawater mixing)
 - **Quantitative Validation:** Poor zone has 66% higher TDS and 330% higher Cl^- than Good zone
-

PART B: GROUNDWATER FLOW MODELLING AND ZONE BUDGET

- **Software:** MODFLOW-6 within ModelMuse 4.4.3
 - **Model Domain:** 352 km²; 107 × 58 grid; 300 m × 300 m cells; 4,954 active cells
 - **Hydrostratigraphic Layers:** 4 layers – Layer 1 (0–45 m, shallow aquifer), Layer 2 (45–150 m, main aquifer), Layer 3 (150–220 m, semi-confined), Layer 4 (220–300 m, basal aquitard)
 - **Simulation Period:** 2001–2020 (20 years); 80 quarterly stress periods
 - **Calibration:** RMSE = 1.24 m; MAE = 0.98 m; Mass balance error < 0.5%
 - **Calibrated Recharge:** 8.5% of mean annual rainfall (378.2 mm)
 - **Water Balance – Inflow:** Recharge = 2.45×10^7 m³ (100%)
 - **Water Balance – Outflow:** Evapotranspiration = 1.18×10^7 m³ (48.2%); Coastal outflow = 1.12×10^7 m³ (45.7%); Pumping = 1.58×10^6 m³ (6.5%)
 - **Storage Change:** Negligible (–0.3%) – near-steady-state
 - **Zone Budget:** 60% of recharge percolates from Layer 1 to Layer 2; 70% from Layer 2 to Layer 3; 50% from Layer 3 to Layer 4
 - **Sustainability Assessment:** Abstraction exceeds sustainable yield
 - **Three Reasons for Unsustainability:**
 - High recharge variability (CV = 61%); in dry years abstraction exceeds recharge by factor of 2+
 - Coastal outflow (45.7%) is not available for abstraction – it maintains the freshwater lens
 - Temporal mismatch between monsoon recharge and year-round demand
 - **Required Reduction:** 30–40% reduction in pumping to stabilise the freshwater lens
-

PART C: SEAWATER INTRUSION ASSESSMENT

- **Software:** SWI2 Package coupled with MODFLOW-6
- **Governing Principle:** Ghyben-Herzberg relation ($z = 40 \times h$)

- **Abstraction Rate:** 5 L/s (sustained)
- **Intrusion Progression (2001–2020):**
 - 2001: 0.0 km (equilibrium)
 - 2005: 1.0 km (Rate: 0.20 km/yr)
 - 2010: 2.4 km (Rate: 0.28 km/yr)
 - 2015: 3.9 km (Rate: 0.30 km/yr)
 - 2020: 6.3 km (Rate: 0.48 km/yr)
- **Critical Threshold:** 2.4 km (reached in 2010) – intrusion accelerates beyond this point
- **Observed Acceleration:** Rate increased from 0.20 km/yr to 0.48 km/yr (more than doubled)
- **Sensitivity Analysis:**
 - Rank 1: Recharge (± 1.5 km for $\pm 15\%$ change) – most influential
 - Rank 2: Pumping rate (± 1.2 km for $\pm 20\%$ change)
 - Rank 3: Hydraulic conductivity (± 1.0 km)
 - Rank 4: Specific yield (± 0.6 km) – least influential
- **Hydrochemical Validation:**
 - Sharp increase in Cl^- and TDS at KC-13 between 2000–2010 matches modelled intrusion advance
 - Persistent high Cl^- and TDS at HPII_KCH_006 confirms permanent intrusion zone
 - Na^+/Cl^- ratios < 0.86 in intrusion zone confirm active seawater mixing
 - Absence of NO_3^- and PO_4^{3-} rules out anthropogenic surface contamination

Projection of Seawater Intrusion to 2025

- **Two Scenarios Developed:** Conservative (Scenario I) and Accelerated (Scenario II)
- **Scenario I – Basis:** Long-term average intrusion rate (0.33 km/yr) over 2001–2020
- **Scenario I – Projected Intrusion by 2025:** ~7.95 km
- **Scenario II – Basis:** Recent accelerated rate (0.66 km/yr) based on observed acceleration (+0.18 km/yr)
- **Scenario II – Projected Intrusion by 2025:** ~9.60 km
- **Range of Probable Intrusion:** 7.95 km – 9.60 km by 2025
- **Affected Areas (Scenario II):** Central villages (Amrapar, Ganeshpar) – threatening ~3,000 residents

- **Difference Between Scenarios:** 1.65 km – represents potential benefit of management intervention
- **Key Message:** Intrusion is no longer a localised coastal phenomenon; it is advancing toward the island's interior

Overall Integration

- **GWPZ (Part A) identifies where** groundwater resources are located and where recharge should be targeted
- **Flow Model (Part B) quantifies how much** water is available and the extent of unsustainability
- **Intrusion Model (Part C) assesses the primary threat** to water quality and projects future trajectory
- **Spatial Correlation:**
 - Western Good zones are the last resilient freshwater resource
 - Central Moderate zones are in the path of the advancing saline front
 - Eastern Poor zones are already beyond natural recovery
- **Urgent Need:** Managed Aquifer Recharge (Chapter 6), abstraction control, and integrated water resource planning (Chapter 7)

CHAPTER 6:

MANAGED AQUIFER RECHARGE STRATEGY FOR KHADIR ISLAND

"From diagnosis to intervention: a scientifically-grounded, community-centred blueprint for groundwater replenishment"

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6.1 INTRODUCTION

Managed Aquifer Recharge (MAR) is the intentional recharge of water to aquifers for subsequent recovery or environmental benefit (Dillon et al., 2020). In the context of Khadir Island, where the hydrogeological assessment presented in Chapter 5 revealed a stressed freshwater lens, accelerating seawater intrusion (6.3 km inland by 2020, projected to reach 7.95–9.60 km by 2025 under business-as-usual conditions), and unsustainable abstraction patterns, MAR represents not merely a desirable intervention but an essential strategy for long-term water security.

This chapter translates the scientific understanding generated in Chapter 5 into a practical, spatially-explicit, and technically-feasible MAR strategy. It presents the rationale for MAR on Khadir Island, the multi-criteria site suitability analysis methodology, the proposed types and locations of MAR structures, their design considerations and material requirements, implementation priorities, and the expected outcomes and sustainability assessment.

The chapter is organised into seven sections. Section 6.2 establishes the rationale for MAR specific to Khadir Island's hydrogeological challenges, including the recharge deficit, the temporal mismatch between supply and demand, and the urgent need for seawater intrusion mitigation in light of the 2025 projection. Section 6.3 describes the multi-criteria site suitability analysis framework. Section 6.4 presents the integration of GWPZ, drainage, and slope data for site selection. Section 6.5 details the proposed MAR structures—their types, locations, design specifications, and material requirements. Section 6.6 outlines implementation priorities aligned with the phased plan. Section 6.7 assesses expected outcomes and long-term sustainability. Section 6.8 summarises the chapter.

6.2 RATIONALE FOR MANAGED AQUIFER RECHARGE IN KHADIR ISLAND

The hydrogeological assessment presented in Chapter 5 established critical findings that collectively justify the need for Managed Aquifer Recharge (MAR) interventions in Khadir Island. These conditions indicate that natural recharge alone is insufficient to maintain long-term groundwater sustainability, making artificial recharge and recharge enhancement measures essential for protecting the freshwater aquifer system of Khadir Island.

6.2.1 The Recharge Deficit

Natural recharge, estimated at 8.5% of mean annual rainfall (approximately 602 mm over the recharge area), is insufficient to balance current abstraction levels of 1,257 ML/year. The sensitivity analysis of the seawater intrusion model (Chapter 5, Section 5.10.3) demonstrated that recharge variability is the most influential control on intrusion dynamics: a

15% increase in effective recharge could reduce seawater intrusion by approximately 1.5 km over a decade. Conversely, a 15% decrease—such as during drought years like 2018 (103 mm rainfall)—could accelerate intrusion by a similar amount. MAR directly addresses this recharge deficit by capturing and infiltrating monsoon runoff that would otherwise be lost to evapotranspiration or coastal discharge.

6.2.2 The Temporal Mismatch Between Supply and Demand

Over 85% of annual recharge occurs during the three-month monsoon period (July to September), while water demand for domestic use, livestock, and agriculture remains relatively constant throughout the year. This creates a severe seasonal deficit, particularly in the pre-monsoon summer months when the June deficit can reach 89% of total demand. MAR structures—particularly check dams and percolation tanks—function by impounding monsoon runoff and releasing it gradually through infiltration, effectively transforming a temporally-concentrated natural input into a distributed year-round resource.

6.2.3 Seawater Intrusion Mitigation

The freshwater lens on Khadir Island is maintained by a delicate balance between recharge and the seaward-directed hydraulic gradient. The seawater intrusion model (Chapter 5, Section 5.10) demonstrated that the saline front has advanced progressively inland, reaching 6.3 km by 2020 under sustained abstraction of 5 L/s, with the intrusion rate accelerating from 0.20 km/yr (2001–2005) to 0.48 km/yr (2015–2020). The projection analysis (Chapter 5, Section 5.12) indicates that, without intervention, the saline front is likely to extend to between approximately 7.95 km and 9.60 km by 2025, depending on future abstraction and recharge conditions. Under the accelerated scenario, the front would encroach upon the central villages of Amrapar and Ganeshpar, directly threatening the domestic water supply and agricultural livelihoods of more than 3,000 residents.

By enhancing recharge in the Good and Moderate groundwater potential zones, MAR can help sustain or restore the hydraulic gradient that pushes back against the saline wedge. The sensitivity analysis (Chapter 5, Section 5.10.3) demonstrated that a 15% increase in effective recharge could reduce seawater intrusion by approximately 1.5 km over a decade, making recharge enhancement the single most effective intervention for intrusion control. Bandharas (tidal regulators) specifically address the coastal dimension by preventing tidal ingress while allowing freshwater outflow, providing a physical barrier against the landward movement of saline water at the coastline itself. Together, inland MAR structures and coastal bandharas form a two-pronged defence against the accelerating threat of seawater intrusion.

6.2.4 Global Precedent

MAR has been successfully implemented in arid and semi-arid regions worldwide. In Australia, managed aquifer recharge schemes in the Murray-Darling Basin have demonstrated recovery efficiencies of 70–90% (Dillon et al., 2020). In Spain, percolation tanks and recharge wells in the Segura Basin have increased groundwater levels by 5–10 m over a decade (Fernández-Escalante et al., 2018). In Gujarat, India, check dams constructed under the Sardar Patel Participatory Water Sanitation Scheme have raised water tables by 3–8 m in downstream wells (CGWB, 2016). These precedents provide confidence that appropriately sited and designed MAR structures can be effective in the Khadir Island context.

6.3 MULTI-CRITERIA SITE SUITABILITY ANALYSIS

The site suitability analysis for Managed Aquifer Recharge (MAR) structures was carried out using a Multi-Criteria Decision Analysis (MCDA) framework integrated within the GIS environment of ArcGIS 10.8. The framework combines the Groundwater Potential Zone (GWPZ) map developed in Chapter 5 with additional hydrogeological, geomorphological, and terrain-based criteria to identify locations suitable for artificial recharge interventions (Rahman et al., 2012; Magesh et al., 2012).

The analytical framework was designed to maximize recharge effectiveness, improve groundwater sustainability, and minimize environmental and economic constraints. The analysis followed a systematic four-step workflow:

1. **Base Screening:** The GWPZ map was used as the primary screening layer. Areas classified as Good and Moderate groundwater potential zones were prioritised for recharge shafts and percolation tanks because of their favourable infiltration and storage characteristics. Check dams and coastal bandharas were considered across all suitable drainage locations because their primary function is runoff interception and temporary water storage.
2. **Drainage and Slope Overlay:** Drainage density, stream network, and flow accumulation maps were integrated with slope analysis to identify locations capable of capturing sufficient monsoon runoff. Low to moderate slope areas were preferred to ensure structural stability and effective infiltration.
3. **Subsurface Suitability Assessment:** Lithology and lineament density layers were analysed to evaluate aquifer permeability and subsurface recharge potential. Areas with sandstone formations, higher fracture density, and favourable secondary permeability were considered more suitable for MAR implementation.

4. **Constraint Mapping:** Exclusion zones were delineated to avoid environmentally and technically unsuitable areas such as built-up land, saline marshes, highly impermeable shale zones, and regions affected by severe seawater intrusion. These constraints were incorporated to improve the long-term effectiveness and sustainability of recharge structures.

The integrated GIS-MCDA framework enabled systematic identification of suitable MAR locations and provided the scientific basis for the recharge planning strategy proposed for Khadir Island.

6.4 INTEGRATION OF GWPZ, DRAINAGE, AND SLOPE DATA

The integration of Groundwater Potential Zone (GWPZ), drainage, and slope data was carried out to identify suitable locations for Managed Aquifer Recharge (MAR) structures across Khadir Island, and the siting criteria adopted for different recharge structures are summarised in Table 6.1.

Table 6.1: Siting Criteria for MAR Structures on Khadir Island

Structure Type	GWPZ	Slope	Additional Criteria
Recharge Shaft	Good/Moderate	—	Near stream beds or lineaments; permeable subsurface lithology (sand/gravel); depth to bypass surface clay layers
Percolation Tank	Good/Moderate	0–5° (flat to gentle)	Permeable soils (sandy loam); adequate drainage area; distance from built-up zones
Check Dam	Any zone with ephemeral stream	2–10° (gentle to moderate)	Flow accumulation 500–5,000 cells; defined stream channel; suitable foundation conditions
Bandhara (Tidal Regulator)	Adjacent to vulnerable freshwater zone	—	Stream mouth at coast; tidal influence zone; upstream of extraction wells; suitable foundation

6.4.1 GWPZ as the Primary Filter

The GWPZ map (Chapter 5, Figure 5.1) serves as the primary filter for MAR site selection. The underlying principle is that MAR structures should be located where the aquifer has the natural capacity to accept, store, and transmit recharged water. Siting a recharge structure in a Poor zone with impermeable shale and steep slopes would result in minimal infiltration and potential wastage of captured runoff.

The spatial integration of GWPZ data with drainage and slope criteria yielded the following observations:

- **Good Zone (26.65 km²):** The western part of the island, with its permeable Kanakavati sandstone, high lineament density, flat slopes, and low drainage density, is ideally suited for deep recharge structures such as recharge shafts and broad-area structures such as percolation tanks.
- **Moderate Zone (285.10 km²):** The central part of the island, with its mixed lithology and moderate infiltration capacity, is suitable for check dams on ephemeral streams and selected percolation tanks where local soil and slope conditions are favourable.
- **Poor Zone (3.45 km²):** The eastern part is generally unsuitable for shallow MAR due to impermeable shale and steep slopes. However, one deep recharge shaft is proposed at Gadhada to investigate the potential of the deeper confined aquifer, and bandharas are proposed along the eastern coast to mitigate saline ingress.

6.4.2 Drainage and Flow Accumulation

The drainage network and flow accumulation map (Chapter 3) were critical for identifying locations where monsoon runoff naturally concentrates, providing the water source for MAR structures. The analysis focused on:

- **Ephemeral Stream Channels:** The primary targets for check dams are 2nd to 4th order streams with defined channels and moderate to high flow accumulation (500–5,000 cells).
- **Drainage Convergence Zones:** Areas where multiple tributaries coalesce are preferred for percolation tanks, as they receive runoff from larger catchment areas.
- **Stream Mouths at the Coast:** The locations where streams discharge into the Rann are the targets for bandharas, as these are the conduits through which tidal saline water enters the island during high tides.

6.4.3 Slope Constraints

Slope is a critical engineering constraint as well as a hydrogeological criterion. Structures on excessively steep slopes are prone to erosion, structural instability, and reduced effectiveness. Structures on excessively flat terrain may lack sufficient hydraulic gradient for water conveyance. The slope criteria applied (Table 6.1) balance these considerations.

The siting criteria for each MAR structure type are summarised in Table 6.1, derived from established guidelines (Aju et al., 2021; Bouwer, 2002; Maliva, 2020; Werner et al., 2013).

6.5 PROPOSED MAR STRUCTURES: TYPES, LOCATIONS, MATERIAL INTERVENTIONS, AND DESIGN CONSIDERATIONS

Four types of Managed Aquifer Recharge (MAR) structures are proposed for Khadir Island based on the hydrogeological conditions, groundwater potential zones, drainage characteristics, slope conditions, and seawater intrusion vulnerability of the study area. The proposed structures include recharge shafts, percolation tanks, check dams, and bandharas (tidal regulators). Each structure serves a specific recharge or salinity-control function and was selected according to local terrain, runoff availability, aquifer characteristics, and engineering feasibility.

The design of the MAR structures was developed considering the hyper-arid climate, saline groundwater conditions, high evapotranspiration, and seasonal runoff availability of Khadir Island (Bouwer, 2002; Dillon et al., 2009). Special emphasis was given to maximizing recharge efficiency, reducing seepage and sedimentation losses, and improving long-term durability under corrosive saline environmental conditions. Corrosion-resistant materials, protective linings, cutoff systems, and desilting arrangements were incorporated to improve operational life and structural stability.

Recharge shafts are proposed in areas where low-permeability clay or shale layers restrict natural infiltration. These shafts directly transmit monsoon runoff into deeper permeable aquifer zones by bypassing the near-surface impermeable layer. The shafts are designed with RCC precast rings, perforated casing within the aquifer zone, gravel packing, filter media, and upstream desilting chambers to minimize clogging and enhance recharge performance. The shafts extend approximately 2–3 m into the underlying permeable formation to improve hydraulic connectivity with the aquifer system. Figure 6.1 presents the typical design consideration of a recharge shaft.

Table 6.2: Description, Dimensions, Function, and Material Requirements of Proposed MAR Structures

Structure Type	Typical Dimensions	Primary Function	Key Material Requirements
Recharge Shaft	Diameter: 1–2 m; Depth: 10–30 m	Recharge deeper aquifer by bypassing clay/shale layers	RCC rings, perforated HDPE/PVC casing, gravel pack, filter media, FRP/polymer-coated cover
Percolation Tank	Area: 0.5–5 ha; Depth: 1–3 m	Store runoff and enhance shallow aquifer recharge	Earthen embankment with clay core, stone pitching, RCC spillway, HDPE/bentonite lining
Check Dam	Height: 1–3 m; Length: 10–50 m	Reduce runoff velocity and increase infiltration	RCC/masonry structure, gabions, cutoff wall, apron, energy dissipation basin
Bandhara (Tidal Regulator)	Height: 1–3 m	Prevent saline tidal ingress	RCC piers, epoxy-coated reinforcement, FRP/stainless steel gates, wing walls, cutoff wall

Percolation tanks are proposed in low-slope areas with suitable drainage catchment and permeable soils. These structures temporarily store monsoon runoff and enhance vertical infiltration into the shallow aquifer system. The embankments are constructed using compacted earthen material with clay cores to minimize seepage losses through the bund. Stone pitching, spillways, stilling basins, and desilting arrangements are incorporated to improve erosion resistance and operational stability. Figure 6.2 illustrates the typical design consideration of a percolation tank.

Check dams are proposed across ephemeral drainage channels to reduce runoff velocity, increase streambed infiltration, and retain freshwater within upstream reaches. The structures are designed with limited heights (generally below 3 m) to reduce construction cost and upstream submergence. RCC, random rubble masonry, and gabion structures are proposed depending on stream size and site conditions. Aprons, cutoff walls, and energy dissipation arrangements are included to prevent scour and piping failure. Figure 6.3 presents the typical design consideration of a check dam.

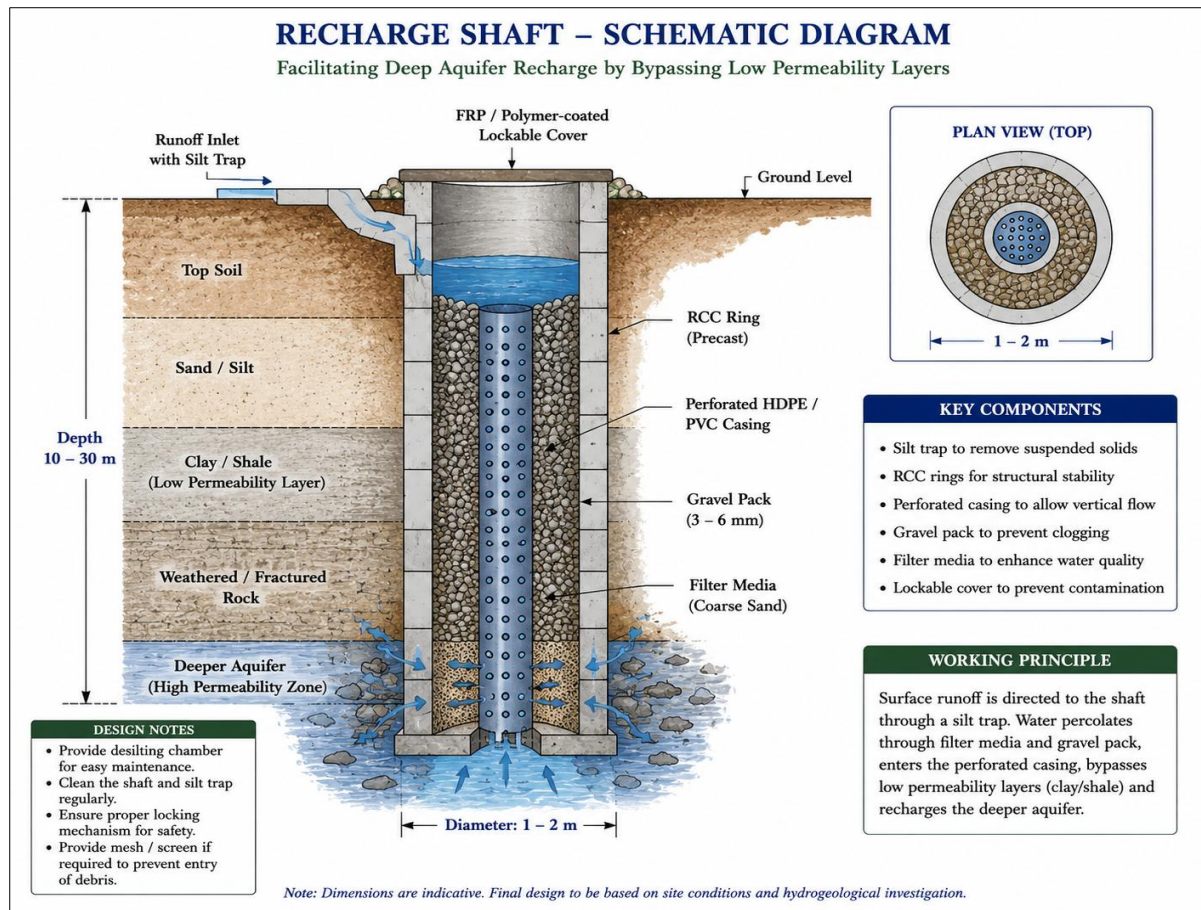


Figure 6.1: Typical Design Consideration of Recharge Shaft

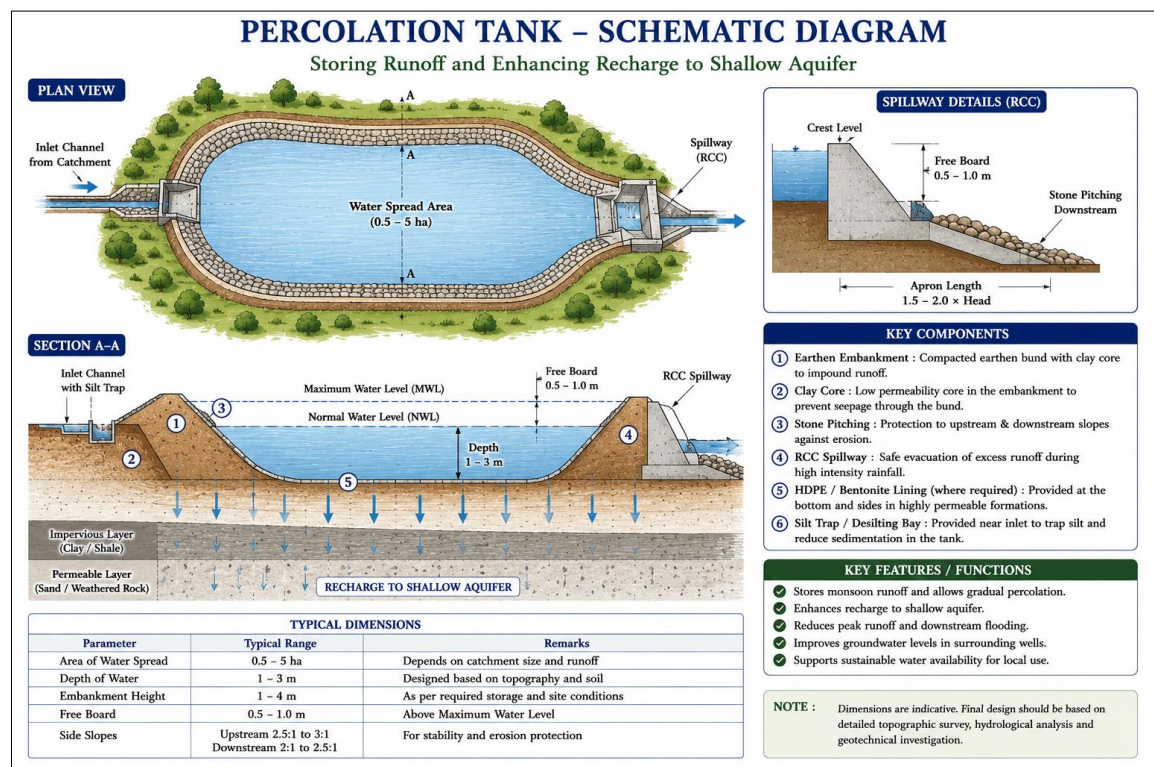


Figure 6.2: Typical Design Consideration of Percolation Tank

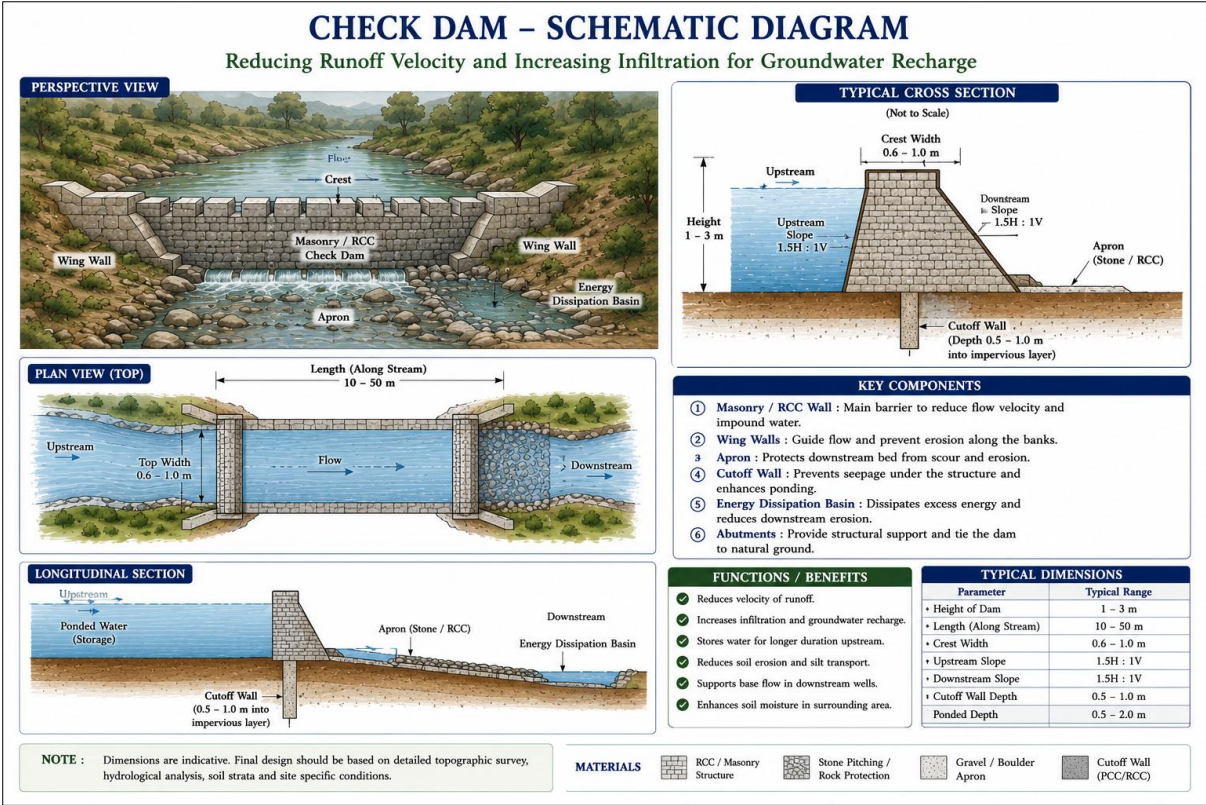


Figure 6.3: Typical Design Consideration of Check Dam

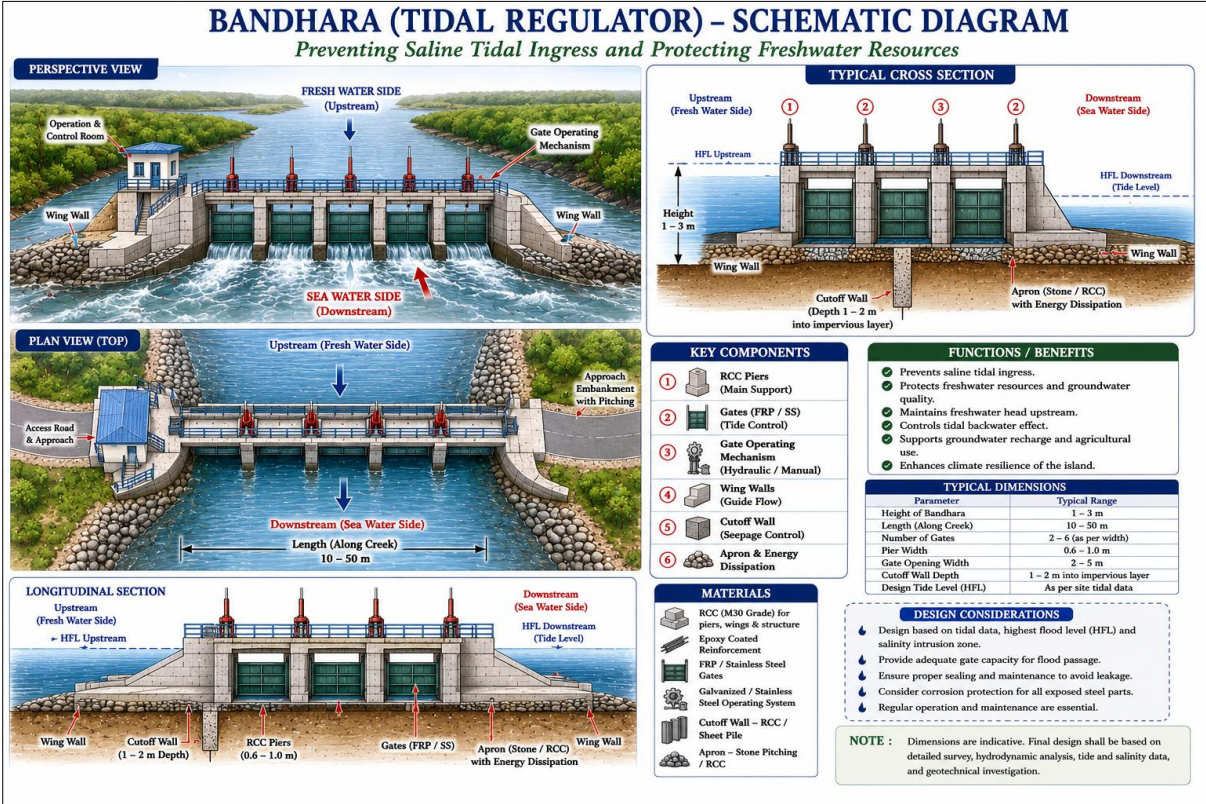


Figure 6.4: Typical Design Consideration of Bandhara

Bandharas (tidal regulators) are proposed near coastal stream mouths to control saline tidal ingress and protect the upstream freshwater lens from seawater intrusion. These structures consist of gated weirs with manually operated or tidal-controlled gates. During the monsoon season, the gates remain open to allow freshwater discharge, whereas during high tides and dry periods, the gates remain closed to prevent saline water intrusion into the inland drainage channels and aquifer system. Reinforced concrete piers, corrosion-resistant gates, wing walls, cutoff walls, and scour protection measures are incorporated into the design. Figure 6.4 shows the typical design consideration of a bandhara.

The suggested materials are adapted considering the salinity intrusion, corrosion risk, seepage losses, and material-performance observations discussed in the attached Khadir Island study, especially the sections on *material-centric interventions*, *polymer composites*, and *corrosion-resistant infrastructure* for arid saline environments.

6.5.3 Proposed Locations of MAR

The proposed 23 locations of Managed Aquifer Recharge (MAR) structures were identified using ArcGIS 10.8 through integrated analysis of Groundwater Potential Zones (GWPZ), groundwater budgeting, seawater intrusion assessment, drainage characteristics, slope conditions, and hydrogeological suitability of Khadir Island.

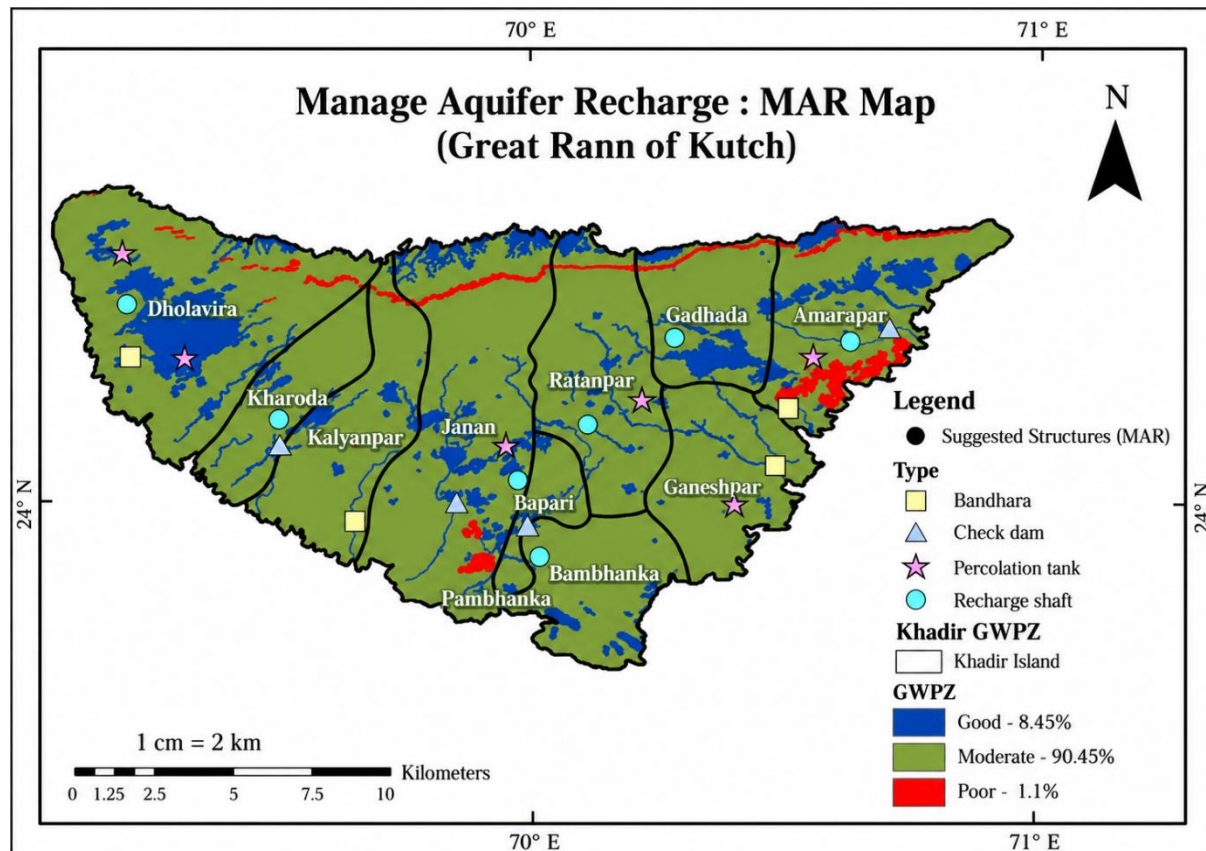


Figure 6.5: Proposed Manage Aquifer Recharge Sites of Khadir Island

Tables 6.3: Proposed locations for the 23 MAR structures, along with their coordinates, GWPZ class, and site-specific characteristics.

Site ID	Structure Type	Village / Location	Latitude (N)	Longitude (E)	GWPZ Class	Design Parameter
RS-1	Recharge Shaft	Ratanpar	23.8675	70.2750	Good	Aquifer depth: 30–50 m
PT-2	Percolation Tank	Ratanpar	23.8730	70.2820	Good	Tank area: 1.5–2.5 ha
RS-3	Recharge Shaft	Janan	23.8500	70.3150	Good	Aquifer depth: 30–50 m
PT-4	Percolation Tank	Janan	23.8550	70.3220	Good	Tank area: 2.0–3.0 ha
RS-5	Recharge Shaft	Janan	23.8420	70.3280	Good	Aquifer depth: 30–50 m
PT-6	Percolation Tank	Dholavira	23.8830	70.2150	Good	Tank area: 1.0–2.0 ha
RS-7	Recharge Shaft	Dholavira	23.8880	70.2220	Good	Aquifer depth: 40–60 m
PT-8	Percolation Tank	Dholavira	23.8750	70.2300	Good	Tank area: 1.5–2.5 ha
PT-9	Percolation Tank	Amrapar	23.7950	70.3670	Moderate	Tank area: 2.0–3.5 ha
RS-10	Recharge Shaft	Amrapar	23.8020	70.3730	Moderate	Aquifer depth: 40–60 m
PT-11	Percolation Tank	Ganeshpar	23.7750	70.3960	Moderate	Tank area: 1.5–2.5 ha

Site ID	Structure Type	Village / Location	Latitude (N)	Longitude (E)	GWPZ Class	Design Parameter
RS-12	Recharge Shaft	Bambhanka	23.7550	70.4130	Moderate	Aquifer depth: 50–70 m
CD-13	Check Dam	Kharoda	23.7680	70.4380	Moderate	Height: 1.5–2.0 m
CD-14	Check Dam	Janan	23.8670	70.3100	Good	Height: 2.0–3.0 m
CD-15	Check Dam	Amrapar	23.8700	70.3600	Moderate	Height: 1.5–2.0 m
CD-16	Check Dam	Bambhanka	23.7570	70.4150	Moderate	Height: 2.0–2.5 m
BH-17	Bandhara	Ratanpar Coast	23.8680	70.2680	Good	Manual gate
BH-18	Bandhara	Dholavira Coast	23.8820	70.2270	Good	Manual gate
BH-19	Bandhara	Amrapar Coast	23.7950	70.3550	Moderate	Manual gate
BH-20	Bandhara	Bambhanka Coast	23.7580	70.4220	Moderate	Manual gate
BH-21	Bandhara	Kalyanpar / Gadhada Coast	23.7180	70.4430	Poor	Automatic tidal gate
CD-22	Check Dam	Bapuari	23.8270	70.3850	Moderate	Height: 1.5–2.0 m
RS-23	Recharge Shaft	Gadhada	23.7100	70.4500	Poor	Deep aquifer: 100–150 m

6.5.4 Summary of Proposed Structures

Table 6.4: Summary of Proposed MAR Structures for Khadir Island

Structure Type	Number	Site IDs
Recharge Shaft (RS)	7	RS-1, RS-3, RS-5, RS-7, RS-10, RS-12, RS-23
Percolation Tank (PT)	6	PT-2, PT-4, PT-6, PT-8, PT-9, PT-11
Check Dam (CD)	5	CD-13, CD-14, CD-15, CD-16, CD-22
Bandhara (BH)	5	BH-17, BH-18, BH-19, BH-20, BH-21
Total	23	

6.5.5 Spatial Distribution Rationale

The spatial distribution of the proposed MAR structures reflects the hydrogeological variability of Khadir Island:

- **Good Zone Priority:** A majority of recharge shafts (4 of 7) and percolation tanks (4 of 6) are located in the good zone (Ratanpar, Janan, Dholavira), where permeable Kanakavati sandstone, high lineament density, flat slopes, and low drainage density maximise the effectiveness of recharge. These areas represent the island's most valuable groundwater resource, and protecting and enhancing them through MAR is the highest priority.
- **Check Dams on Drainage Lines:** All five check dams are located on 2nd to 4th order ephemeral streams with moderate to high flow accumulation (800–2,500 cells), ensuring sufficient runoff capture during monsoon events. The check dams in the Good zone (CD-14 at Janan) are larger (2–3 m height), while those in the Moderate zone are smaller (1.5–2.5 m), reflecting the greater recharge potential in the Good zone.
- **Bandharas at Coastal Stream Mouths:** All five bandharas are positioned at the mouths of streams where they meet the Rann. Those adjacent to the Good zone (BH-17 at Ratanpar, BH-18 at Dholavira) are prioritised for protecting the most valuable freshwater resource. BH-21 at Kalyanpar/Gadhada is proposed with an automatic tidal-operated gate to manage the higher tidal range and more persistent saline conditions in the eastern sector.
- **Targeted Intervention in Poor Zone:** One deep recharge shaft (RS-23 at Gadhada) is proposed to explore the potential of the deeper confined aquifer, which may contain palaeochannel deposits with brackish but treatable water (Bhadra et al., 2021). This is combined with a bandhara (BH-21) to mitigate saline ingress at the coast.

6.6 Summary of Chapter 6

This chapter has presented a comprehensive Managed Aquifer Recharge (MAR) strategy for Khadir Island, translating the hydrogeological assessment findings from Chapter 5 into a practical, spatially-explicit intervention plan.

The strategy is grounded in a clear rationale: natural recharge (8.5% of rainfall) is insufficient to balance current abstraction; there is a severe temporal mismatch between monsoon recharge and year-round demand; and the freshwater lens is threatened by accelerating seawater intrusion (6.3 km inland by 2020, projected to reach 7.95–9.60 km by 2025 under business-as-usual conditions). MAR directly addresses all three challenges. A multi-criteria site suitability analysis, integrating the GWPZ map (Good, Moderate, Poor zones) with drainage, slope, lineament density, and soil data, identified 23 suitable locations for four types of MAR structures:

1. **7 Recharge Shafts** — Vertical structures designed to bypass low-permeability surface layers and deliver water directly to deeper permeable aquifers. Constructed with concrete rings, gravel packs, and filter media. Five are located in Good/Moderate zones; one deep shaft (RS-23) is proposed at Gadhada to explore palaeochannel potential.
2. **6 Percolation Tanks** — Shallow impoundments (0.5–5 ha, 1–3 m depth) designed to maximise vertical infiltration across broad areas. Constructed with earthen embankments, clay cores, stone pitching, and spillways. Four are located in the Good zone.
3. **5 Check Dams** — Low-height barriers (1–3 m) across ephemeral streams with moderate to high flow accumulation (800–2,500 cells). Constructed with cement concrete, boulder masonry, or gabions. Two are in the Good zone; three in the Moderate zone.
4. **5 Bandharas (Tidal Regulators)** — Gated structures at coastal stream mouths designed to block tidal saline ingress while allowing monsoon freshwater outflow. Constructed with RCC piers, steel gates, and stone masonry wing walls. Two protect the Good zone; three protect Moderate/Poor zones.

The site selection is scientifically grounded, with structures prioritised in the Good and Moderate groundwater potential zones where the underlying aquifer has the capacity to accept, store, and transmit recharged water. The spatial distribution reflects the hydrogeological variability of the island, targeting the western recharge zones for maximum impact while providing protective interventions along the eastern coast.

The implementation phasing, expected outcomes including the anticipated 90 MLY of additional groundwater recharge, reduction in seawater intrusion, improvement in groundwater quality, and the sustainability assessment covering technical, financial, institutional, and environmental dimensions are integrated into the broader Integrated Water Resource Development Plan presented in Chapter 8.

CHAPTER 7:

WATER DEMAND, AVAILABILITY, AND STRESS ASSESSMENT

"Quantifying the balance: sectoral demand trends, supply variability, and water stress projections for Khadir Island"

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7.1 INTRODUCTION

A comprehensive understanding of water demand trends, groundwater availability, and the resulting stress on freshwater resources is essential for sustainable water resource management in arid and coastal environments (UNESCO, 2020; FAO, 2012). The hydrogeological investigations and numerical modelling presented in Chapter 5 established that the aquifer system of Khadir Island is under severe environmental stress. The freshwater lens is thin (approximately 15–25 m thick) and highly vulnerable to depletion, groundwater abstraction locally exceeds sustainable recharge conditions, and seawater intrusion has progressively advanced inland from the coastal margins (Custodio, 2010; Werner et al., 2013). Numerical modelling indicated that the saline front migrated approximately 6.3 km inland by 2020, with projected advancement reaching nearly 7.95–9.60 km by 2025 under continued abstraction and variable recharge conditions. These hydrogeological constraints are further intensified by the socio-economic dependence of nearly 17,000 inhabitants on groundwater-supported livelihoods, including agriculture, pastoralism, handicrafts, and tourism.

This chapter evaluates the demand side of the groundwater balance and examines the relationship between water demand, water availability, and water stress conditions across Khadir Island. The analysis first quantifies historical and projected sector-wise water demand trends for domestic, livestock, agricultural, and tourism sectors during the period 2001–2041 using census data, agricultural statistics, FAO water requirement guidelines, and tourism growth records (Allen et al., 1998; CPHEEO, 2019). Subsequently, post-monsoon groundwater availability for the period 2011–2025 is assessed using rainfall variability, groundwater recharge estimates, and groundwater storage conditions derived from the Water Table Fluctuation (WTF) method (Healy and Cook, 2002). Finally, future groundwater stress conditions for the period 2026–2030 are evaluated using the Water Stress Index (WSI) framework, which relates total water demand to available freshwater resources (UNESCO, 2020; Gain et al., 2022). The chapter provides the quantitative and conceptual basis for the Integrated Water Resource Development Plan proposed in Chapter 8.

The chapter is organised into seven sections. Section 7.2 synthesises the major hydrogeological and water resource constraints identified in the preceding chapters. Section 7.3 presents sector-wise water demand trends and future demand projections. Section 7.4 evaluates post-monsoon groundwater availability under varying rainfall conditions. Section 7.5 presents the Water Stress Index analysis and future stress projections. Section 7.6 discusses the supply–demand relationship and its implications for sustainable groundwater management. Finally, Section 7.7 summarises the major findings of the chapter.

7.2 SYNTHESIS OF KEY CONSTRAINTS

The integrated assessment across the preceding chapters reveals six interconnected constraints that define the water resource challenge on Khadir Island.

7.2.1 Physical Constraints

1. **Inherent salinity of shallow aquifer:** Due to marine transgression (~18,000 years ago), the shallow sediments are fine-grained and saline-saturated. TDS ranges from approximately 1,200 mg/L in the west (Dholavira) to >7,000 mg/L in the east (Kalyanpar).
2. **Thin and stressed freshwater lens:** The lens thickness is only 15–25 m, and water levels have declined significantly. Well KC-13 at Dholavira went completely dry in 2015. Pre-monsoon heads are now less than 0.5 m amsl in many areas.
3. **Seawater intrusion:** The saline front advanced from 1 km (2005) to 6.3 km (2020), with the intrusion rate accelerating from 0.20 km/yr to 0.48 km/yr. The critical threshold was crossed at 2.4 km (2010). Projections indicate 7.95–9.60 km intrusion by 2025.
4. **Temporal supply-demand mismatch:** Approximately 85–90% of recharge occurs in three monsoon months (July–September), while demand is relatively constant year-round. The pre-monsoon deficit (April–June) is severe.
5. **Inefficient water use:** Flood irrigation (the dominant method) has an application efficiency of only 60%, meaning 40% of abstracted water is lost to seepage and evaporation.

7.2.2 Socio-Economic Constraints

1. **Livelihood dependence on water:** Pastoralism contributes 82% of the regional economy. Agriculture occupies 34% of land use. Tourism is growing rapidly. All are highly water-dependent.
2. **Infrastructure gaps:** No desalination plant exists. Piped water supply is intermittent. Only two long-term monitoring wells serve the entire island.
3. **Data scarcity:** The sparse monitoring network limits model calibration, but the multi-line validation strategy provides sufficient confidence for planning.

7.3 WATER DEMAND TRENDS (2001–2041)

Water demand on Khadir Island was calculated for four sectors: domestic, livestock, agriculture, and tourism. Historical demand for 2001, 2011, and 2021 was calculated based on

census data, livestock statistics, agricultural land use, and tourism records. Future demand for 2031 and 2041 was projected using decadal growth trends.

7.3.1 Domestic Water Demand

Domestic water demand was assessed for a 20-year period (2001–2021) to understand the trend in water requirements due to population growth. Population data for 2001 and 2011 were obtained from the Census of India, while the 2021 population was projected based on the decadal growth rate observed between 2001 and 2011.

According to Census data, the total population of Khadir Island increased from 13,050 in 2001 to 15,006 in 2011, representing an increase of 1,956 persons and a decadal growth rate of 15%. Using this growth rate, the 2021 population was estimated as 17,257. Domestic water demand was calculated using 135 litres per capita per day (LPCD), as recommended by CPHEEO guidelines for rural water supply planning.

Table 7.1: Domestic Water Demand of Khadir Island (2001–2021)

Year	Population	Growth Rate (%)	Water Demand (MLD)	Annual Demand (MLY)	MCM
2001	13,050	—	1.762	643.13	0.643
2011	15,006	15.00	2.026	739.49	0.739
2021	17,257	15.00	2.330	850.45	0.850

Sources: Census of India (2011); projected to 2021 at 1.5% CAGR; CPHEEO guidelines.

The domestic water demand of Khadir Island increased from 1.76 MLD in 2001 to 2.33 MLD in 2021, reflecting population growth over the past two decades. This increasing trend highlights the need for sustainable drinking water supply planning.

7.3.2 Livestock Water Demand

Livestock plays a significant role in the livelihood of communities on Khadir Island. The livestock population for 2001 and 2011 was obtained from census records, while the 2021 livestock population was projected based on the decadal growth rate of 15%.

According to census records, the total livestock population in Khadir Island was 14,143 in 2001 and 16,265 in 2011. Based on the decadal growth rate of 15%, the livestock population for 2021 was estimated as 18,707. Livestock water demand was calculated using standard water consumption norms recommended by FAO: 68.25 LPCD for cattle and buffalo, and 13.6 LPCD for sheep and goat.

Table 7.2: Livestock Water Demand of Khadir Island (2001–2021)

Year	Livestock Population	Growth Rate (%)	Water Demand (MLD)	Annual Demand (MLY)	MCM
2001	14,143	—	0.565	206.23	0.206
2011	16,265	15.00	0.651	237.61	0.238
2021	18,707	15.00	0.749	273.39	0.273

Sources: District Animal Husbandry Department (2010); FAO (2010).

The results indicate that livestock water demand increased from 0.565 MLD in 2001 to 0.749 MLD in 2021, showing a gradual increase in livestock-based water requirements.

7.3.3 Agricultural Water Demand

Agriculture in Khadir Island is primarily controlled by erratic rainfall, saline soil conditions, and limited freshwater availability. Agricultural practices are largely dependent on monsoon rainfall during the Kharif season, while Rabi and Summer crops are cultivated selectively using groundwater resources.

Field surveys and farmer interactions indicate that bajra, jeera, vegetables, fodder, and fruits are the major crops cultivated. Crop water requirements were estimated using the FAO-56 methodology, resulting in a total annual crop water requirement of 163 cm.

Table 7.3: Crop Water Requirement by Season

Sr. No.	Crop	Season	Water Requirement (cm)	Seasonal Requirement (cm)	Total Requirement (cm)
1	Bajra	Kharif	20	43	163
2	Jeera	Kharif	75		
3	Vegetables	Kharif	40		
4	Fodder	Kharif	40		
5	Fruits	Kharif	40		
6	Vegetables	Rabi	60	60	
7	Fodder	Rabi	60		
8	Fruits	Rabi	60		
9	Vegetables	Summer	80	60	
10	Fodder	Summer	80		
11	Fruits	Summer	80		

Source: Agriculture Department, Kachchh; farmer interviews (2020–21); FAO-56.

Agricultural land use was derived from LULC analysis for the years 2000, 2010, and 2020. The agricultural water demand remained relatively stable over the 20-year period.

Table 7.4: Agricultural Water Demand of Khadir Island (2000–2020)

Year	Agricultural Area (km ²)	Net Demand (MCM/year)	Gross Demand (MCM/year)
2000	106.79	174.07	290.12
2010	109.43	178.36	297.27
2020	106.79	174.07	290.12

The average gross agricultural demand, considering 60% irrigation efficiency, is estimated as 292.50 MCM/year. Agriculture constitutes the largest share of total water demand, highlighting the need for efficient irrigation practices.

7.3.4 Tourism Water Demand

Khadir Island has emerged as an important tourism destination due to Dholavira (UNESCO World Heritage Site since 2021) and the Rann Utsav. A scientific tourism demand model was developed based on the Equivalent Population Method, considering average tourist inflow, stay duration, seasonal tourism days, and per capita water demand of 150 LPCD (CPHEEO guidelines).

Table 7.5: Tourism Water Demand Estimation for Khadir Island (2001–2021)

Year	Tourist Arrival (Annual)	Average Stay (Days)	Tourism Season (Days/Year)	Equivalent Population	Water Demand (LPCD)	Water Demand (MLD)	Annual Demand (MCM)
2001	3,000	1.5	90	12	150	0.002	0.001
2011	20,000	1.5	120	82	150	0.011	0.004
2021	75,000	2	120	411	150	0.062	0.023

Notes: Equivalent Population = (Tourist Arrival × Average Stay) / 365; Tourism growth assumed at 15% per decade; Tourism mainly concentrated near Dholavira.

The tourism water demand for Khadir Island increased gradually from 0.002 MLD in 2001 to 0.062 MLD in 2021. Although tourism demand remains relatively small compared to agricultural demand, it is expected to increase significantly in the future.

7.3.5 Total Water Demand (2001–2041)

Total water demand was estimated by combining domestic, livestock, agricultural, and tourism water requirements over a 40-year period (2001–2041). Historical demand for 2001,

2011, and 2021 was calculated based on recorded data. Future demand for 2031 and 2041 was projected using decadal growth trends.

Table 7.6: Total Water Requirement of Khadir Island (2001–2041)

Year	Domestic (MCM)	Livestock (MCM)	Agriculture (MCM)	Tourism (MCM)	Total Water Demand (MCM)
2001	0.643	0.206	290.12	0.001	290.97
2011	0.739	0.238	297.27	0.004	298.25
2021	0.850	0.273	290.12	0.023	291.27
2031	0.978	0.314	291.13	0.026	292.45
2041	1.125	0.361	291.13	0.030	292.65

Sources: Census of India (projected); CPHEEO; FAO; Agriculture Department, Kachchh.

The total water demand of Khadir Island is projected to increase from 290.97 MCM in 2001 to 292.65 MCM in 2041. Agriculture remains the dominant water-consuming sector throughout the study period, accounting for more than 99% of total water demand. Domestic, livestock, and tourism demands show gradual increases due to population growth and tourism development.

7.4 POST-MONSOON WATER AVAILABILITY (2011–2025)

Post-monsoon water availability is a critical indicator of groundwater security in Khadir Island because the freshwater resources of the island depend predominantly on recharge derived from southwest monsoon rainfall (CGWB, 2020; Healy and Cook, 2002). The shallow aquifer system receives nearly 85–90% of its annual recharge during the monsoon period between July and September, making monsoon rainfall variability the principal controlling factor of annual groundwater availability. In arid and semi-arid island environments, post-monsoon groundwater storage represents the primary freshwater reserve that sustains domestic, livestock, agricultural, and tourism water demand throughout the dry season (FAO, 2012; UNESCO, 2020).

7.4.1 Methodology

Post-monsoon groundwater availability for the period 2011–2025 was estimated using three primary components: rainfall, groundwater recharge, and aquifer storage conditions.

1. **Rainfall data:** Annual rainfall data were obtained from the India Meteorological Department (IMD, 2022) gridded rainfall dataset. Rainfall variability was analysed to evaluate its influence on groundwater recharge and post-monsoon storage conditions.

2. **Groundwater recharge:** Groundwater recharge was estimated using the Water Table Fluctuation (WTF) method, which is widely applied for unconfined aquifer systems exhibiting seasonal groundwater-level variation (Healy and Cook, 2002). The recharge was estimated using the following relationship:

$$\text{Recharge} = \text{Specific Yield} \times \text{Water Level Rise}$$

where groundwater-level rise represents the difference between pre-monsoon and post-monsoon groundwater levels, and specific yield represents the drainable porosity of the aquifer material.

3. **Dead storage:** Dead storage represents the volume of groundwater stored below the post-monsoon water table that remains available for abstraction during the dry season. This component is important in arid environments because it provides the residual freshwater reserve that sustains water supply during prolonged dry periods and delayed monsoon conditions. The total water available after the post-monsoon season was computed as:

$$\text{Total Water Available (MLY)} = \text{Groundwater Recharge (ML)} + \text{Dead Storage (ML)}$$

The groundwater availability assessment utilised long-term observation well data from the Dholavira and Kalyanpar monitoring wells operated by government agencies. The Dholavira observation well contains continuous groundwater records from 1990 onwards and therefore provides a reliable long-term dataset for analysing temporal groundwater behaviour. In contrast, the Kalyanpar observation well was installed more recently, and reliable data are available only from 2010 onwards. Owing to the absence of comparable long-term datasets for both locations before 2010, the study adopted 2010 as the common base year for integrated groundwater recharge, availability, and demand assessment.

The adoption of a common reference period (2010–2025) ensures consistency, comparability, and reliability in the interpretation of groundwater trends across Khadir Island. This approach minimises temporal inconsistencies between datasets and provides a scientifically defensible basis for groundwater budgeting, Water Stress Index (WSI) analysis, and future water resource planning.

7.4.2 Water Availability Results

The analysis of post-monsoon groundwater availability for the period 2011–2025 reveals pronounced interannual variability in freshwater resources across Khadir Island. Total water availability varied from approximately 1,256 MLY during severe dry years to more than 2,324 MLY during high-rainfall years, indicating strong dependence of groundwater recharge

on monsoon precipitation. The observed fluctuations are primarily controlled by the highly variable southwest monsoon rainfall, which exhibited a coefficient of variation (CV) of approximately 61%, characteristic of arid and semi-arid climatic regions (IMD, 2022; Healy and Cook, 2002).

Years receiving high monsoon rainfall generated substantial groundwater recharge and higher post-monsoon water levels, whereas drought years produced limited recharge and significantly reduced groundwater availability. This high climatic variability demonstrates that groundwater availability in Khadir Island is highly uncertain and strongly rainfall-dependent, increasing the vulnerability of the freshwater lens to seasonal water stress and seawater intrusion.

Table 7.7: Post-Monsoon Water Availability of Khadir Island (2011–2025)

Year	Rainfall (mm)	Water Level Rise (m)	Groundwater Recharge (ML)	Dead Storage (ML)	Total Water Available (MLY)
2011	932	3.5	1,099.18	1,224.80	2,323.98
2012	255	1.5	471.08	910.75	1,381.83
2013	507	3.0	942.16	1,202.82	2,144.97
2014	383.9	2.1	659.51	659.51	1,319.02
2015	684	3.4	1,067.78	1,138.44	2,206.21
2016	416	2.7	832.24	950.01	1,782.24
2017	449	1.4	444.38	1,028.52	1,472.90
2018	103	1.1	345.46	1,012.82	1,358.27
2019	186	1.3	408.27	1,185.55	1,593.81
2020	282	2.0	628.10	1,209.10	1,837.20
2021	350	2.3	722.32	1,099.25	1,821.57
2022	400	2.6	816.53	1,162.00	1,978.53
2023	650	3.3	1,036.37	1,224.80	2,261.17
2024	200	1.2	376.86	879.34	1,256.20
2025	420	2.7	847.94	1,162.00	2,009.94

Sources: IMD gridded rainfall data; CGWB water level records; author's calculations.

7.4.3 Key Observations

- **Highest water availability:** 2,323.98 MLY in 2011 (932 mm rainfall, 3.5 m water level rise)

- **Lowest water availability:** 1,256.20 MLY in 2024 (200 mm rainfall)
- **Critical year:** 2018 recorded the lowest rainfall (103 mm) and lowest water level rise (1.1 m)
- **Inter-annual variability:** The difference between wet and dry years is approximately 1,068 MLY (an 85% increase in wet years)

7.4.4 Comparison of Wet and Dry Years

Table 7.8: Comparison of Wet and Dry Year Water Availability Extremes

Parameter	Wet Year (2011)	Wet Year (2023)	Dry Year (2018)	Dry Year (2024)
Rainfall (mm)	932	650	103	200
Water Level Rise (m)	3.5	3.3	1.1	1.2
Groundwater Recharge (ML)	1,099.18	1,036.37	345.46	376.86
Dead Storage (ML)	1,224.80	1,224.80	1,012.82	879.34
Total Availability (MLY)	2,323.98	2,261.17	1,358.27	1,256.20

The comparison reveals that wet years show total availability exceeding 2,260 MLY, while dry years show availability below 1,360 MLY. The availability gap between wet and dry years is approximately 1,000–1,068 MLY.

7.4.5 Implications for Water Resource Management

1. **Drought Vulnerability:** Dry year 2024 shows total availability of only 1,256.20 MLY, which is insufficient to meet annual demand, confirming that drought conditions can push the island into water deficit.
2. **Storage Requirement:** To bridge dry year deficits, a minimum storage capacity of approximately 150–200 ML is needed to capture wet year surpluses through MAR structures.
3. **MAR Prioritisation:** Wet years like 2011 (2,323.98 MLY) provide a surplus of approximately 900–1,000 MLY above demand. Without MAR, this surplus is lost to coastal outflow (~45% of recharge) and evapotranspiration.
4. **Effective Usable Supply:** The effective usable supply is significantly lower than total availability due to the temporal mismatch, the coastal outflow requirement for lens maintenance, and water quality constraints (TDS >2,500 mg/L is not usable for drinking).

7.5 WATER STRESS INDEX (WSI) RESULTS (2026–2030)

The Water Stress Index (WSI) is defined as the ratio of total water demand to total available water resources, serving as a key indicator for assessing the sustainability of water use (UNESCO, 2023; Gain et al., 2022). The Water Stress Index (WSI) is widely used to evaluate the sustainability of water resource utilisation by comparing total water demand with total available freshwater resources (UNESCO, 2023; Gain et al., 2022). The index provides an integrated measure of water scarcity and reflects the pressure exerted on available water resources under varying climatic and socio-economic conditions. In groundwater-dependent regions such as Khadir Island, the WSI is particularly useful for evaluating future vulnerability to groundwater depletion, drought conditions, and seawater intrusion.

The WSI values were interpreted using standard classification thresholds commonly adopted in global water stress assessments (UNESCO, 2023). The index is interpreted using standard threshold values:

- **WSI < 0.5:** Low water stress
- **$0.5 \leq \text{WSI} < 0.8$:** Moderate stress
- **$0.8 \leq \text{WSI} < 1.0$:** High stress
- **WSI ≥ 1.0 :** Critical water stress

Based on the observed trends in groundwater availability and sector-wise water demand during the period 2011–2025, future WSI conditions for Khadir Island were projected for the period 2026–2030 under varying rainfall scenarios. The analysis integrates projected groundwater demand with estimated groundwater availability under normal, wet, and dry monsoon conditions to evaluate the future sustainability of groundwater resources.

7.5.1 Projected Water Demand (2026–2030)

Table 7.9: Projected Total Water Demand of Khadir Island (2026–2030)

Year	Total Water Demand (MLY)
2026	1,390.19
2027	1,410.87
2028	1,431.68
2029	1,452.64
2030	1,473.75

Projected total water demand for the period 2026–2030 was estimated using population growth trends, livestock demand projections, agricultural water requirements, and tourism growth patterns. The results indicate a gradual increase in total annual water demand over the

projection period due to increasing domestic requirements and tourism development, although agriculture remains the dominant water-consuming sector.

7.5.2 Projected Water Availability (2026–2030)

Projected groundwater availability for the period 2026–2030 was estimated using historical rainfall–recharge relationships and varying monsoon rainfall scenarios derived from observed climatic variability in the study area (IMD, 2022). The analysis considered normal, above-normal, dry, and wet rainfall conditions to evaluate the sensitivity of groundwater availability to monsoon fluctuations.

The results demonstrate significant variability in freshwater availability between wet and dry years, reflecting the strong dependence of Khadir Island on monsoon recharge conditions.

Table 7.10: Projected Water Availability Under Varying Rainfall Scenarios

Year	Rainfall (mm)	Scenario	Total Water Available (MLY)
2026	380	Normal	1,852.85
2027	550	Above Normal	2,158.95
2028	250	Dry	1,358.21
2029	400	Normal	1,978.53
2030	600	Wet	2,229.80

7.5.3 Water Stress Index Results (2026–2030)

The projected Water Stress Index (WSI) values for Khadir Island during the period 2026–2030 are presented in Table 7.11. The results indicate considerable interannual variability in water stress conditions, primarily controlled by monsoon rainfall and corresponding groundwater recharge. The WSI values range from 0.65 to 1.05, demonstrating that the island remains under persistent moderate to critical groundwater stress conditions throughout the projection period.

Table 7.11: Water Stress Index (WSI) for Khadir Island (2026–2030)

Year	Water Demand (MLY)	Water Availability (MLY)	WSI	Stress Category
2026	1,390.19	1,852.85	0.75	Moderate to High
2027	1,410.87	2,158.95	0.65	Moderate
2028	1,431.68	1,358.21	1.05	Critical
2029	1,452.64	1,978.53	0.73	Moderate
2030	1,473.75	2,229.80	0.66	Moderate

7.5.4 Interpretation of WSI Results:

The WSI projections for 2026–2030 reveal several critical insights:

- **Moderate stress prevails in normal and wet years:** WSI values of 0.65–0.75 indicate that the island's water resources are under persistent pressure even under favourable rainfall conditions.
- **Critical stress in dry years:** The WSI of 1.05 in 2028 (a projected dry year) indicates that water demand would exceed total available supply, pushing the island into a water deficit situation.
- **High vulnerability to drought:** The sharp increase from WSI 0.65 (2027, above-normal rainfall) to WSI 1.05 (2028, dry year) demonstrates the extreme sensitivity of the island's water security to monsoon variability.
- **No low-stress years:** Even in the wettest projected year (2030, 600 mm rainfall), the WSI remains at 0.66 (Moderate stress), indicating that the island never achieves a comfortable water surplus under current abstraction and demand patterns.

7.6 SUPPLY-DEMAND GAP ANALYSIS

The comparison between projected water demand and post-monsoon groundwater availability reveals significant supply–demand imbalances across Khadir Island. Although the annual groundwater balance appears positive under normal and wet rainfall conditions, detailed seasonal and hydrogeological analysis indicates that the effective usable freshwater resource is substantially lower than the total recharge estimated for the island (Custodio, 2010; Werner et al., 2013).

7.6.1 Annual Scale Analysis

At the annual scale, total post-monsoon groundwater availability ranges between approximately 1,256 and 2,324 MLY, whereas projected annual water demand varies from approximately 1,390 to 1,474 MLY. Superficially, this suggests that groundwater availability exceeds annual demand in most years. However, this apparent surplus is misleading due to several hydrogeological and water-quality constraints.

- First, there is a strong temporal mismatch between recharge and demand. Nearly 85–90% of groundwater recharge occurs during the southwest monsoon period (July–September), whereas domestic, agricultural, livestock, and tourism water demands continue throughout the year (Healy and Cook, 2002). Consequently, groundwater extracted during the dry season is not adequately replenished until the following monsoon.

- Second, a substantial proportion of groundwater recharge is required to maintain the hydraulic equilibrium of the freshwater lens against seawater intrusion. Numerical groundwater budget analysis presented in Chapter 5 demonstrated that approximately 45% of total recharge is lost as lateral coastal outflow toward the Rann. This coastal discharge is hydrologically necessary because it maintains seaward freshwater gradients that resist inland migration of saline groundwater (Bear et al., 1999). Therefore, a significant portion of recharge cannot be considered available for sustainable abstraction.
- Third, groundwater quality limitations further reduce the volume of usable freshwater. Large parts of the aquifer system exhibit Total Dissolved Solids (TDS) exceeding 2,500 mg/L, particularly in eastern Khadir Island affected by seawater intrusion. Such groundwater is unsuitable for drinking purposes and only marginally suitable for irrigation, thereby reducing the effective freshwater availability for human use (WHO, 2017).

7.6.2 Seasonal Scale Analysis

Seasonal analysis reveals the true severity of groundwater stress conditions in Khadir Island. During the pre-monsoon period (April–June), groundwater levels decline to their annual minimum while agricultural and domestic water demand reaches peak levels. Under these conditions, the monthly groundwater deficit may reach approximately 89% of total seasonal demand, particularly during drought years and delayed monsoon conditions.

The severe pre-monsoon deficit results in intensive groundwater abstraction from the already stressed freshwater lens. Continuous over-extraction during this period reduces freshwater heads and accelerates seawater intrusion from the coastal margins toward the interior of the island (Werner et al., 2013). The seasonal imbalance between recharge and demand therefore represents the principal driver of groundwater depletion, declining water quality, and long-term aquifer degradation in Khadir Island.

The analysis demonstrates that annual groundwater availability alone is not an adequate indicator of water security in arid coastal environments. Sustainable groundwater management in Khadir Island requires seasonal storage enhancement, recharge conservation, Managed Aquifer Recharge (MAR), efficient irrigation practices, and regulation of groundwater abstraction to reduce dry-season groundwater stress.

7.7 Summary of Chapter 7

This chapter has presented a comprehensive water demand, availability, and stress assessment for Khadir Island. The key findings are:

1. **Water demand** increased from 290.97 MCM in 2001 to 291.27 MCM in 2021 and is projected to reach 292.65 MCM by 2041. Agriculture accounts for more than 99% of total demand, highlighting the critical importance of irrigation efficiency improvements.
2. **Domestic demand** increased from 1.76 MLD (2001) to 2.33 MLD (2021), driven by population growth from 13,050 to 17,257.
3. **Livestock demand** increased from 0.565 MLD (2001) to 0.749 MLD (2021), reflecting the central role of pastoralism in the island's economy.
4. **Tourism demand**, while currently small (0.062 MLD in 2021), is growing rapidly and is concentrated in the dry winter season when water availability is lowest.
5. **Post-monsoon water availability** exhibits extreme interannual variability, ranging from 1,256 MLY (dry year 2024) to 2,324 MLY (wet year 2011). This variability is directly controlled by monsoon rainfall ($CV = 61\%$).
6. **Water Stress Index** projections for 2026–2030 range from 0.65 (Moderate) to 1.05 (Critical). Dry years push the island into critical water stress, with demand exceeding total available supply.
7. **The supply-demand gap** is most severe at the seasonal scale, with pre-monsoon deficits reaching 89% of demand. The apparent annual surplus is not available for abstraction due to coastal outflow requirements and water quality constraints.

These findings underscore the urgent need for demand-side management (particularly in agriculture), supply augmentation through managed aquifer recharge, and the development of alternative water sources. These interventions form the core of the Integrated Water Resource Development Plan presented in Chapter 8.

CHAPTER 8:

**INTEGRATED WATER RESOURCE DEVELOPMENT PLAN FOR
KHADIR ISLAND**

**"From diagnosis to action: a community-centred blueprint for water
security on Khadir Island"**

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8.1 INTRODUCTION

The preceding chapters have established a comprehensive scientific understanding of the water crisis facing Khadir Island. The hydrogeological assessment (Chapter 5) revealed a stressed freshwater lens, unsustainable abstraction patterns, and accelerating seawater intrusion projected to reach 7.95–9.60 km inland by 2025. The Managed Aquifer Recharge Strategy (Chapter 6) identified 23 suitable locations for water conservation structures. The water demand and stress assessment (Chapter 7) demonstrated that the Water Stress Index ranges from 0.65 (Moderate) in normal years to 1.05 (Critical) in dry years, with agriculture accounting for more than 99% of total demand.

This chapter translates these scientific findings into a practical, phased, and community-centred Integrated Water Resource Development Plan for Khadir Island. The plan is designed to be replicable for the other isolated bays of the Great Rann of Kachchh with appropriate local adjustments. It combines demand-side and supply-side interventions and a monitoring framework into a coherent 10-year roadmap for achieving water security.

8.2 VISION AND GUIDING PRINCIPLES

8.2.1 Vision Statement

"A water-secure Khadir Island where the freshwater lens is stabilised, seawater intrusion is halted, livelihoods are sustained and diversified, and communities actively manage their water resources through a blend of traditional knowledge and modern science."

8.2.2 Guiding Principles

1. **Demand Management First:** Prioritise reduction of water losses, particularly in agriculture where flood irrigation has an efficiency of only 60%. Demand reduction is more cost-effective and environmentally sustainable than supply augmentation alone.
2. **Nature-Based Solutions:** Promote interventions that work with natural hydrological processes—check dams, percolation tanks, bandharas, and revival of traditional water harvesting structures.
3. **Community Participation:** Engage local stakeholders at every stage of planning, implementation, and monitoring. Establish Village Water User Associations (VWUAs) to ensure local ownership and long-term sustainability.
4. **Adaptive Management:** Design a flexible planning framework that responds to monitoring data, climate variability, and changing socio-economic conditions.

5. **Replicability:** Ensure the framework is documented for application to other inhabited bets of the Great Rann of Kachchh and similar arid island aquifers globally.

8.2.3 Alignment with Sustainable Development Goals

The proposed Integrated Water Resource Development Plan for Khadir Island is strongly aligned with the United Nations Sustainable Development Goals (SDGs), particularly those related to water security, climate resilience, environmental sustainability, and livelihood protection in vulnerable arid regions. The framework integrates scientific assessment, sustainable groundwater management, and community-oriented planning to support long-term socio-ecological sustainability.

- **SDG 6 (Clean Water and Sanitation):** By targeting a 27% reduction in water demand and an additional 60 MLY of groundwater recharge, the plan supports Target 6.4 (substantially increase water-use efficiency and ensure sustainable freshwater withdrawals) and Target 6.5 (implement integrated water resources management). The provision of reliable water supply for domestic, livestock, and agricultural needs directly advances Target 6.1 (universal and equitable access to safe drinking water).
- **SDG 13 (Climate Action):** The plan strengthens the resilience of Khadir Island to climate variability and extreme events, particularly droughts and saline intrusion, by enhancing natural recharge, controlling seawater intrusion through bandharas, and establishing adaptive management triggers based on real-time monitoring data. This aligns with Target 13.1 (strengthen resilience and adaptive capacity to climate-related hazards).
- **SDG 15 (Life on Land):** By promoting nature-based solutions—percolation tanks, gabion check dams, piloodi cultivation, and revival of traditional water harvesting structures—the plan sustains the ecological integrity of the island's rangelands and agricultural soils. It ensures that water resource development does not degrade the land but instead enhances its long-term productivity, supporting pastoralism and traditional livelihoods.

Overall, the Integrated Water Resource Development Plan adopts a holistic and sustainable approach that balances groundwater utilisation, recharge enhancement, ecological conservation, and socio-economic development. The framework is therefore consistent with the broader principles of sustainable development, ensuring that present water demands are addressed without compromising the needs and resource security of future generations.

8.3 PHASED IMPLEMENTATION FRAMEWORK (2026–2035)

The Integrated Water Resource Development Plan for Khadir Island is proposed as a **5 phased 10-year** implementation framework (2026–2035) to ensure gradual, technically feasible, and community-oriented groundwater management (Gale, 2005; UNESCO, 2020). The framework combines groundwater recharge enhancement, seawater intrusion control, demand-side management, and livelihood diversification in a sequential manner. Each phase contains specific objectives, interventions, and measurable performance targets to support adaptive and sustainable water resource management.

8.3.1 Phase 1: Awareness and Preparation (2026–2027)

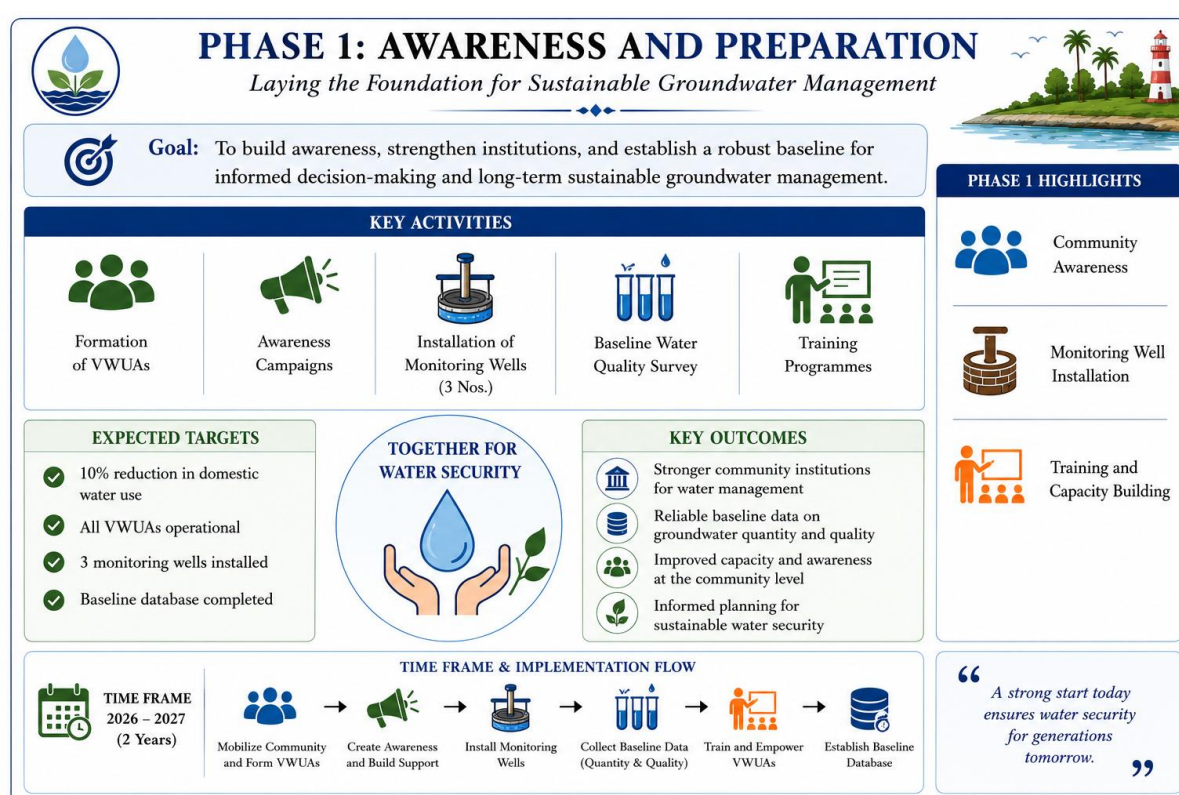


Figure 8.1: Expected Target and Expected Outcomes of Phase:1

Focus: Community mobilisation, institutional strengthening, and baseline monitoring.

During the initial phase, emphasis will be placed on creating awareness regarding groundwater conservation and establishing the institutional and monitoring framework necessary for long-term implementation (FAO, 2012). Village Water User Associations (VWUAs) will be formed across all ten villages to encourage participatory groundwater governance. Groundwater monitoring infrastructure will be strengthened through the installation of new observation wells along the coast-to-interior freshwater gradient. Baseline

groundwater quality and abstraction data will also be generated to support future assessment and decision-making (CGWB, 2020).

8.3.2 Phase 2: Pilot Interventions (2027–2029)

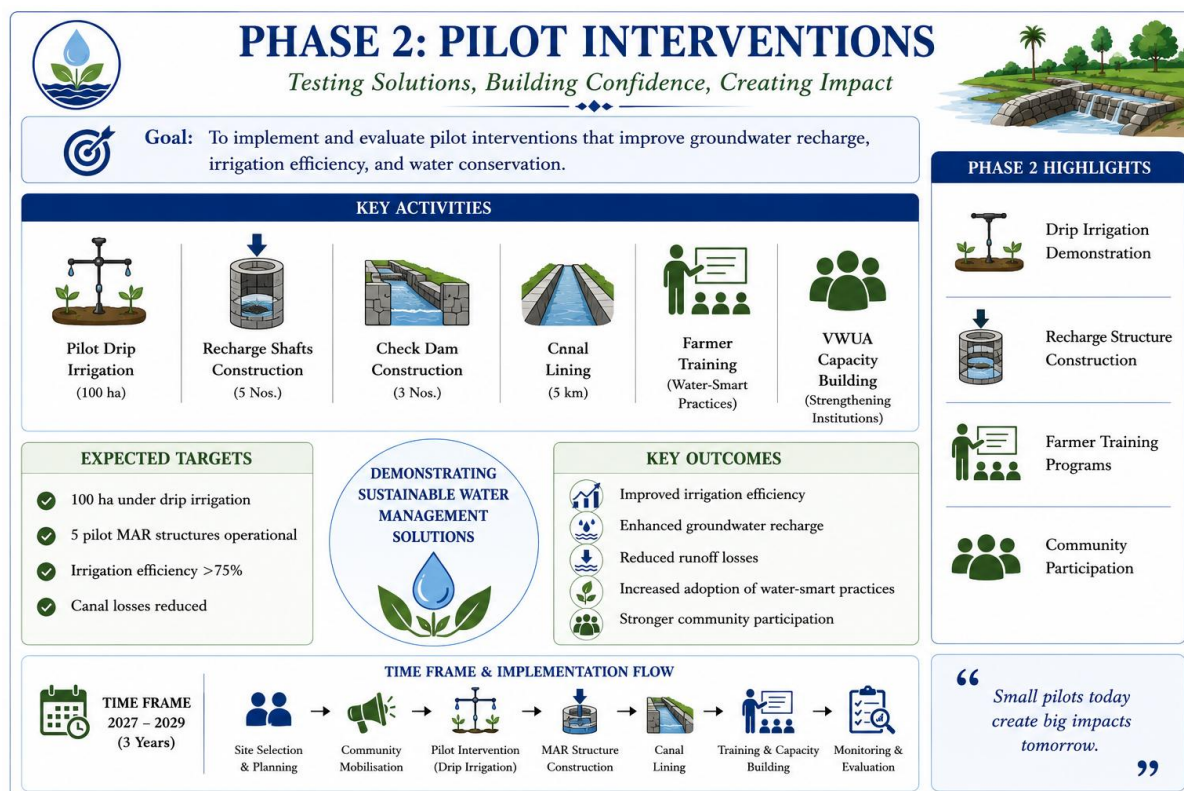


Figure 8.2: Expected Target and Expected Outcomes of Phase:2

Focus: Demonstration of recharge enhancement and water-saving technologies.

The second phase focuses on demonstrating the effectiveness of Managed Aquifer Recharge (MAR) structures and efficient irrigation systems through pilot-scale implementation (Bouwer, 2002; Dillon et al., 2009). Initial recharge structures will be constructed in Good and Moderate groundwater potential zones identified in Chapter 6. Simultaneously, pilot drip irrigation projects will be introduced to reduce agricultural groundwater abstraction and improve irrigation efficiency (Allen et al., 1998).

8.3.3 Phase 3: Coastal Protection (2028–2030)

Focus: Seawater intrusion control and regulated abstraction.

This phase prioritises protection of the freshwater lens through the construction of tidal regulators (bandharas) and implementation of controlled groundwater abstraction policies (Werner et al., 2013; Custodio, 2010). Coastal hydraulic gradients will be stabilised by reducing excessive pumping in vulnerable zones and by improving recharge retention upstream of the coastal interface.



Figure 8.3: Expected Target and Expected Outcomes of Phase:3

8.3.4 Phase 4: Scaling Up (2029–2032)

Focus: Full-scale recharge enhancement and deep aquifer investigation.

The fourth phase involves large-scale expansion of recharge infrastructure across Khadir Island. All proposed MAR structures identified through GIS-MCDA analysis will be completed (Magesh et al., 2012). In addition, deep exploratory boreholes will be drilled to investigate the potential of palaeochannel aquifers as alternative freshwater sources (Bhadra et al., 2021).

8.3.5 Phase 5: Long-Term Sustainability (2031–2035)

Focus: Sustainable livelihoods and long-term groundwater security.

The final phase focuses on ensuring that groundwater management gains are sustained through community participation, livelihood diversification, and maintenance of recharge infrastructure (UNESCO, 2020). Salt-tolerant crops and sustainable tourism development will be promoted to reduce pressure on groundwater resources while improving local income opportunities. Promotion of piloodi (*Salvadora persica*) cultivation represents a nature-based adaptation strategy suitable for saline environments of the Great Rann of Kachchh.

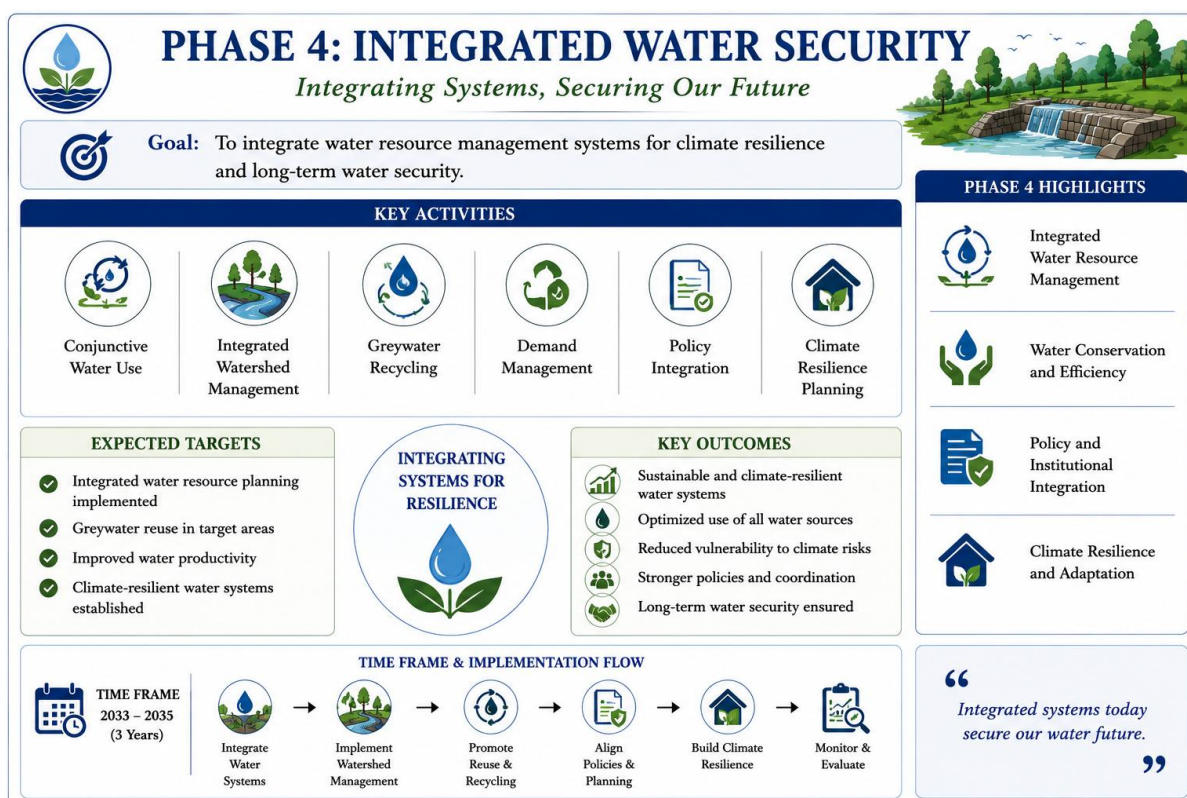


Figure 8.4: Expected Target and Expected Outcomes of Phase:4



Figure 8.5: Expected Target and Expected Outcomes of Phase:5

8.4 MANAGED AQUIFER RECHARGE (MAR) IMPLEMENTATION PLAN

The implementation of the 23 Managed Aquifer Recharge (MAR) structures identified in Chapter 6 has been integrated within the phased implementation framework to ensure systematic execution, technical feasibility, and long-term sustainability (Bouwer, 2002; Dillon et al., 2009). The phased approach prioritises pilot-scale recharge interventions during the initial stages, followed by coastal protection measures and full-scale recharge enhancement across Khadir Island.

Table 8.2: Phase-Wise Implementation of Proposed MAR Structures

Phase	Implementation Period	Proposed Structures	No. of Structures
Phase 2	2027–2029	CD-14 (Janan), CD-15 (Amrapar), CD-22 (Bapuari); RS-1 (Ratanpar), RS-7 (Dholavira)	5
Phase 3	2028–2030	BH-17, BH-18, BH-19, BH-20, BH-21	5
Phase 4	2029–2032	RS-3, RS-5, RS-10, RS-12, RS-23; PT-2, PT-4, PT-6, PT-8, PT-9, PT-11; CD-13, CD-16	13
Phase 5	2031–2035	Operation, maintenance, desilting, and monitoring of all MAR structures	-

Note: CD = Check Dam; RS = Recharge Shaft; PT = Percolation Tank; BH = Bandhara (Tidal Regulator).

The implementation sequence was designed to ensure that recharge structures with high recharge efficiency and lower implementation risk are executed during the initial stages. Pilot recharge shafts and check dams proposed in Good and Moderate groundwater potential zones during Phase 2 are intended to demonstrate recharge effectiveness, improve groundwater levels locally, and enhance community participation in groundwater conservation activities.

Phase 3 prioritises coastal protection through the construction of tidal regulators (bandharas) to reduce seawater intrusion along vulnerable coastal margins (Werner et al., 2013). These structures are expected to stabilise freshwater hydraulic gradients and restrict saline tidal ingress into inland drainage channels and shallow aquifers.

Phase 4 represents the full-scale implementation stage during which all remaining recharge shafts, percolation tanks, and check dams will be completed. Special emphasis is given to Recharge Shaft RS-23 at Gadhada, which is proposed as a deep exploratory recharge structure to investigate the freshwater potential of deeper palaeochannel aquifers identified in the hydrogeological assessment.

Phase 5 focuses on long-term operation, maintenance, and performance monitoring of all MAR structures through Village Water User Associations (VWUAs). Periodic desilting, structural inspection, groundwater-level monitoring, and recharge efficiency assessment will be necessary to ensure long-term sustainability and operational effectiveness of the recharge system.

8.5 Demand-Side and Supply-Side Interventions

The sustainable management of groundwater in Khadir Island requires both reduction in groundwater demand and enhancement of groundwater recharge. Therefore, integrated demand-side and supply-side interventions are proposed to improve water-use efficiency, increase recharge, and control seawater intrusion (FAO, 2012; Werner et al., 2013).

8.5.1 Demand-Side Interventions

Agriculture accounts for more than 99% of total water demand and offers the largest potential savings. The primary intervention is converting from flood irrigation (60% efficiency) to drip irrigation (85–90% efficiency).

Table 8.3: Demand Reduction Targets by Sector

Sector	Current Demand (MLY)	Target Demand (MLY)	Reduction (%)	Primary Intervention
Domestic	148.2	118.6	20	Leak repair, rainwater harvesting, awareness
Agricultural	1,097.5	768.3	30	Drip irrigation (80% of area)
Livestock	64.3	64.3	0	Maintain current levels
Tourism	8.5	8.5	0	Maintain; offset through off-season distribution
Total	1,318.4	959.7	27	-

Domestic Sector (20% Reduction): Current demand of 148.2 MLY is based on 135 LPCD for a population of 17,257. A reduction of 29.6 MLY will be achieved through repair of leaking pipes and taps (saving 10–15% of current use), installation of rooftop rainwater harvesting systems for non-potable water needs such as washing and cleaning, and community awareness campaigns promoting water conservation behaviours. These are low-cost, proven interventions implemented through VWUAs.

Agricultural Sector (30% Reduction): Current gross demand of 1,097.5 MLY arises from a net crop water requirement of 174.07 MCM/year divided by flood irrigation efficiency of 60%, meaning 40% of all applied water is lost to deep percolation, evaporation, and runoff. The reduction of 329.2 MLY will be achieved by converting 80% of irrigated area (approximately 85 km²) to drip irrigation with 85–90% efficiency. The weighted average system efficiency improves to 80%, reducing the gross requirement to 217.59 MCM/year. Drip irrigation also increases crop yields by 15–30%, reduces fertiliser costs through fertigation, and minimises soil salinisation. Implementation is phased: 100 ha in Phase 2, 150 ha in Phase 3, and remainder in Phase 4.

Livestock Sector (0% Reduction): Demand is maintained at 64.3 MLY, based on 18,707 livestock with FAO-recommended consumption norms. Livestock drinking water is essential for animal health. Pastoralism contributes 82% to the regional economy, and reducing water supply would directly impact milk production and household incomes. While demand is not reduced, solar-powered water points will be established along traditional migration routes to improve water access for herds.

Tourism Sector (0% Reduction, Seasonal Distribution): Demand is maintained at 8.5 MLY, based on 75,000 annual visitors consuming 150 LPCD. Tourism is strategically important, with Dholavira's UNESCO status attracting 150,000 visitors annually. Rather than reducing tourism water allocation, the plan focuses on extending the tourist season beyond the current November–February peak through development of off-season attractions. This distributes water demand more evenly across the year, reducing the seasonal concentration that coincides with the dry pre-monsoon period.

Overall: Overall, the proposed demand-side interventions are expected to reduce total annual water demand from approximately 1,318.4 MLY to nearly 959.7 MLY, resulting in total savings of approximately 358.7 MLY. Agriculture contributes nearly 92% of the total projected water savings, highlighting the critical importance of irrigation efficiency improvements in long-term groundwater sustainability.

8.5.2 Supply-Side Interventions

Supply augmentation is achieved primarily through MAR structures. Table 8.4 summarises the additional water supply expected from each intervention type.

The 23 MAR structures together are expected to contribute approximately 60 MLY of additional groundwater recharge. Check dams intercept monsoon runoff in ephemeral streams, reducing flow velocity and enhancing streambed infiltration. Percolation tanks impound runoff over broad areas, maximising vertical infiltration through permeable soils. Recharge shafts bypass low-permeability surface layers and deliver water directly to deeper aquifer zones. Bandharas prevent tidal saline ingress at coastal stream mouths, protecting the existing freshwater lens from further degradation. Together, these structures form an integrated recharge network that captures a significant portion of monsoon runoff that would otherwise be lost to evapotranspiration and coastal discharge.

Table 8.4: Additional Water Supply from MAR Structures

Intervention	Number	Additional Supply (MLY)	Implementation Phase
Check Dams	5	25	Phase 2 and 4
Recharge Shafts	7	15	Phase 2 and 4
Percolation Tanks	6	20	Phase 4
Bandharas	5	Protects existing supply from saline ingress	Phase 3
Total	23	60	

8.6 MONITORING AND EVALUATION FRAMEWORK

A robust monitoring and evaluation framework is essential for assessing the effectiveness of the Integrated Water Resource Development Plan and ensuring adaptive groundwater management in Khadir Island (UNESCO, 2020). The framework focuses on monitoring groundwater availability, water quality, abstraction trends, irrigation efficiency, and community participation through measurable performance indicators and predefined adaptive management triggers.

8.6.1 Key Performance Indicators

A robust monitoring framework is essential for tracking progress, identifying deviations from expected outcomes, and enabling adaptive management. Table 8.5 presents the key performance indicators across four domains.

Table 8.5: Key Performance Indicators for the Integrated Plan

Domain	Indicator	Baseline (2025)	Target (2030)	Frequency
Water Availability	Pre-monsoon water level (average)	~7–10 m bgl	<8 m bgl (stabilised)	Quarterly
	Seawater intrusion distance	6.3 km	<7.0 km (no further advance)	Annual
	MAR structures operational	0	23 (100%)	Quarterly
Water Quality	Na ⁺ /Cl ⁻ ratio in eastern wells	0.56–0.58	>0.86	Quarterly
	TDS in central village wells	Variable	10–30% reduction	Quarterly
Water Use	Total annual abstraction	~1,370 MLY	<1,000 MLY	Annual
	Irrigation efficiency	60%	>75%	Annual
	Drip irrigation coverage	0 ha	80% of irrigated area	Annual
Community	Household water satisfaction	~35%	>80%	Annual survey

8.6.2 Adaptive Management Triggers

Adaptive management is an essential component of sustainable groundwater governance in Khadir Island because the island's hydrogeological system is highly sensitive to rainfall variability, groundwater abstraction, and seawater intrusion processes (Werner et al., 2013; UNESCO, 2020). Owing to the dynamic nature of coastal aquifer systems, management interventions must remain flexible and responsive to changing groundwater conditions rather than relying on fixed long-term assumptions. Continuous monitoring of groundwater levels, water quality, abstraction rates, and Water Stress Index (WSI) conditions is therefore necessary to evaluate whether the implemented interventions are achieving the intended objectives.

To support this approach, predefined trigger levels and corresponding corrective actions have been incorporated into the Integrated Water Resource Development Plan. These triggers are designed to provide early warning of worsening groundwater stress conditions and

to enable timely implementation of management responses before irreversible aquifer degradation occurs. The adaptive management framework particularly focuses on critical indicators such as groundwater depletion, seawater intrusion advancement, declining Na^+/Cl^- ratios, and drought conditions, which collectively represent the principal threats to freshwater security in Khadir Island. The plan includes predefined triggers for corrective action based on monitoring data.

Table 8.6: Adaptive Management Triggers

Trigger Level	Condition	Corrective Action
Warning	WSI exceeds 0.8 for two consecutive quarters	Review abstraction permits; increase awareness campaigns; prioritise MAR maintenance
Critical	WSI exceeds 1.0; or intrusion advances >0.5 km in one year	Implement emergency abstraction restrictions (30% reduction); fast-track bandhara repairs
Drought	Annual rainfall <200 mm	Activate drought contingency plan; prioritise drinking water over irrigation

8.6.3 Annual Participatory Review

An Annual Participatory Review will be conducted each November (post-monsoon) to assess progress, review monitoring data, and adjust the annual work plan. Participants include VWUA representatives from all ten villages, technical staff from CGWB and GWRDC, and relevant government department officials. The review agenda includes presentation of monitoring data, assessment of MAR structure status, review of demand reduction achievements, and formulation of the work plan for the following year.

8.7 EXPECTED OUTCOMES AND SUSTAINABILITY ASSESSMENT

The Integrated Water Resource Development Plan is designed not only to address immediate groundwater stress conditions but also to establish a long-term framework for sustainable water security in Khadir Island. The combined implementation of Managed Aquifer Recharge (MAR), demand-side management, seawater intrusion control, and community-based groundwater governance is expected to improve the resilience of the freshwater aquifer system under future climatic and hydrological uncertainties (UNESCO, 2020; Werner et al., 2013).

8.7.1 Anticipated Outcomes

The successful implementation of the Integrated Water Resource Development Plan is expected to yield the following outcomes by 2035:

1. **Stabilised Freshwater Lens:** Freshwater head increased by 0.2–0.5 m in the Good and Moderate zones, strengthening the seaward hydraulic gradient that resists seawater intrusion.
2. **Controlled Seawater Intrusion:** Intrusion front stabilised at less than 7.0 km from the coastline, compared to the projected 7.95–9.60 km under business-as-usual conditions. This represents prevention of 1.0–2.6 km of additional saline advance into the island's interior.
3. **Reduced Water Stress:** Water Stress Index maintained below 0.75 in normal rainfall years and below 1.0 in dry years, eliminating the critical stress conditions projected under the no-intervention scenario.
4. **Enhanced Groundwater Recharge:** Additional 60 MLY of recharge through 23 MAR structures, improving water availability during the critical dry season and the pre-monsoon period when the deficit is most severe.
5. **Improved Irrigation Efficiency:** Drip irrigation covering 80% of irrigated area, reducing agricultural water demand by 30% while maintaining or improving crop yields through more precise water and nutrient delivery.
6. **Diversified and Resilient Livelihoods:** Piloodi cultivation providing salt-tolerant alternative income for farmers; extended tourist season reducing seasonal economic vulnerability; reliable water supply supporting the pastoralist economy that contributes 82% of regional income.

8.7.2 Sustainability Dimensions

Technical Sustainability: MAR structures are designed for robustness and low maintenance using locally available materials. Check dams using gabion construction and percolation tanks with earthen embankments can be built and maintained with local labour. The primary maintenance requirement is periodic desilting of percolation tanks and check dam impoundments every 3–5 years, a task well within the capacity of trained VWUAs.

Environmental Sustainability: The plan works with natural hydrological processes rather than against them. Nature-based solutions—percolation tanks, gabion check dams, and bandharas—integrate structures into the landscape with minimal disruption to ecosystems. The revival of traditional water harvesting structures, including the Harappan reservoirs at

Dholavira, reinforces cultural connections to water management while providing functional recharge benefits. By enhancing natural recharge rather than importing external water sources, the strategy minimises energy requirements and environmental footprint.

Social Sustainability: Community participation at all stages—from planning through implementation to monitoring—ensures local ownership and accountability. The integration of traditional knowledge, including pastoralist migration patterns and piloodi cultivation, respects and strengthens existing adaptive practices. The focus on livelihood enhancement ensures that water security translates into tangible improvements in household well-being.

8.8 SUMMARY OF CHAPTER 8

This chapter has presented a comprehensive Integrated Water Resource Development Plan for Khadir Island, synthesising the hydrogeological assessment (Chapter 5), the Managed Aquifer Recharge Strategy (Chapter 6), and the water demand and stress assessment (Chapter 7) into a coherent, actionable, 10-year roadmap spanning 2026–2035.

The plan is guided by a vision of water security achieved through demand management, nature-based solutions, community participation, adaptive management, and replicability. It is directly aligned with the United Nations Sustainable Development Goals, particularly SDG 6 (clean water and sanitation) through efficient water use and sustainable withdrawals, SDG 13 (climate action) through enhanced resilience to drought and saline intrusion, and SDG 15 (life on land) through nature-based solutions that sustain rangelands and agricultural soils. This alignment ensures that the plan not only addresses the immediate water crisis but also contributes to the long-term environmental, social, and economic sustainability of the island.

It is structured into five implementation phases:

- **Phase 1 — Awareness and Preparation (Years 1–2):** Community mobilisation, VWUA formation, monitoring network expansion, and baseline surveys.
- **Phase 2 — Pilot Interventions (Years 2–4):** 100 hectares of drip irrigation, 5 pilot MAR structures, canal lining, and farmer training.
- **Phase 3 — Coastal Protection (Years 3–5):** Construction of 5 bandharas, regulated abstraction, and intrusion stabilisation below 7.0 km.
- **Phase 4 — Scaling Up (Years 4–7):** Completion of all 23 MAR structures, palaeochannel exploration, and 80% drip irrigation coverage.

- **Phase 5 — Long-Term Sustainability (Years 5–10):** Piloodi cultivation, traditional structure restoration, off-season tourism, and annual participatory reviews.

The plan targets a 27% reduction in total water demand through a 30% reduction in agricultural water use (via drip irrigation on 80% of irrigated area) and a 20% reduction in domestic water use (via leak repair, rainwater harvesting, and awareness). Supply augmentation of 60 MLY is achieved through 23 MAR structures: 5 check dams, 7 recharge shafts, 6 percolation tanks, and 5 bandharas.

A comprehensive monitoring framework with nine key performance indicators across water availability, water quality, water use, and community satisfaction domains, supported by predefined adaptive management triggers, ensures that the plan remains responsive to changing conditions.

The plan provides a replicable blueprint for the other isolated bays of the Great Rann of Kachchh and for similar arid island aquifers globally facing the combined challenges of groundwater depletion, seawater intrusion, and climate variability.

CHAPTER 9:

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

"What we learned, what we contributed, and what must be done next"

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9.1 INTRODUCTION

This study set out to develop an integrated geo-hydrological approach towards a sustainable water resource development plan for the isolated islands of the Great Rann of Kachchh, with a primary focus on Khadir Island. The research combined remote sensing and GIS-based groundwater potential mapping, numerical groundwater flow and seawater intrusion modelling, hydrogeochemical validation, socio-economic assessment, water demand and availability analysis, managed aquifer recharge strategy, and a phased implementation framework.

This final chapter synthesises the principal findings, states the original contributions to knowledge, and provides actionable recommendations for policy makers, water managers, and future researchers. The chapter is organised into five sections. Section 9.2 summarises the key findings from each chapter. Section 9.3 states the original contributions to knowledge. Section 9.4 provides recommendations for water resource management, policy makers, and future research. Section 9.5 presents the concluding remarks.

9.2 PRINCIPAL RESEARCH FINDINGS OF THE STUDY

The present study developed an integrated geo-hydrological assessment of Khadir Island, Great Rann of Kachchh (GRK), by combining field investigations, RS-GIS-based groundwater potential assessment, numerical groundwater modelling, seawater-intrusion analysis, hydrogeochemical validation, water-demand and stress assessment, and Managed Aquifer Recharge (MAR) planning. The principal findings are presented below, highlighting the hydrogeological behaviour of the island, its major water-resource constraints, and the management implications emerging from the integrated analysis.

9.2.1 Study Area and Field Investigations (Chapter 4):

Khadir Island covers approximately **315 km²** and represents a hyper-arid and hydrogeologically vulnerable environment within the GRK. Mean annual rainfall is approximately **419.8 mm**, with high interannual variability (**CV $\approx$ 61%**), while potential evapotranspiration reaches approximately **2,140 mm/year**. The shallow groundwater system comprises Quaternary alluvial sediments underlain by Jurassic sandstone and shale formations, with a relatively thin **15–25 m freshwater lens** that is highly sensitive to recharge and abstraction.

The island supports approximately **17,000 people across ten villages**, with pastoralism, agriculture, handicrafts and tourism forming the major livelihood activities. Groundwater

remains the principal source of freshwater for domestic, agricultural, livestock and tourism requirements.

Field investigations conducted during the **post-monsoon periods of 2019 and 2021** provided ground-truth information from eight representative wells. Groundwater-quality observations demonstrated considerable spatial variability, with TDS ranging from approximately **250 mg/L in the western sector to 4,900 mg/L in the eastern sector**. Lithological and structural observations confirmed the importance of sandstone formations, shale intercalations, faults and fractures in controlling groundwater occurrence and movement. Long-term observations from the **KC-13 well at Dholavira** and **HP11_KCH_006 at Kalyanpar** further demonstrated a marked contrast between the relatively recoverable western groundwater system and the persistently saline eastern system.

9.2.2 Hydrogeological Assessment (Chapter 5):

Part A: Groundwater Potential Zoning

An integrated **RS-GIS-MIF approach** was applied using eight thematic layers to delineate groundwater potential zones. Drainage density received the highest MIF weight (**22.6%**), followed by land use/land cover (**19.4%**), while geomorphology, lineament density and soil type each contributed **16.1%**.

The resulting groundwater potential map classified the island into:

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

Long-term hydrochemical observations supported this spatial classification. The Good Zone well at Dholavira showed comparatively better and recoverable groundwater quality, whereas the Kalyanpar well in the Poor Zone exhibited persistently high salinity.

Part B: Groundwater Flow Modelling and Zone Budget

A transient three-dimensional **MODFLOW-6** model was developed for **2001–2020**, comprising 107 rows, 58 columns and four hydrostratigraphic layers. Calibration against available monitoring data achieved **RMSE of 1.24 m**, **MAE of 0.98 m**, and a mass-balance error of less than **0.5%**.

The groundwater budget indicated recharge of approximately **$2.45 \times 10^7 \text{ m}^3$** , with major water losses through evapotranspiration (**48.2%**), coastal outflow (**45.7%**) and pumping

(6.5%). Zone-budget analysis further indicated that approximately **60% of recharge percolates towards deeper layers**, demonstrating the important role of vertical groundwater transfer within the aquifer system.

The analysis also highlighted the vulnerability of the present groundwater regime to the combined effects of **high recharge variability, sustained abstraction and the seasonal mismatch between recharge and water demand**.

Part C: Seawater Intrusion Assessment

The **SWI2 density-dependent sharp-interface model** demonstrated progressive inland migration of the saline front under sustained abstraction. The simulated intrusion increased from approximately **1.0 km in 2005 to 2.4 km in 2010, 3.9 km in 2015 and 6.3 km in 2020**. The corresponding intrusion rate increased from **0.20 km/year during 2001–2005 to 0.48 km/year during 2015–2020**, indicating an accelerating trend.

An intrusion distance of approximately **2.4 km** was identified as a critical management threshold. Sensitivity analysis indicated that **recharge variability was the most influential control** on intrusion behaviour. Hydrogeochemical indicators, including TDS, chloride concentration and Na^+/Cl^- ratios, provided independent support for the simulated salinisation trend.

Two projection scenarios for 2025 estimated an intrusion distance of approximately **7.95 km under the conservative scenario and 9.60 km under the accelerated scenario**, indicating the potential for further inland movement of saline groundwater in the absence of effective management interventions.

9.2.3 Managed Aquifer Recharge Strategy (Chapter 6):

The groundwater-potential assessment was integrated with drainage, slope, lineament-density and soil characteristics to identify suitable locations for **Managed Aquifer Recharge (MAR)**. A total of **23 MAR sites** were identified, comprising:

- **7 Recharge Shafts** for transferring recharge water through relatively low-permeability surface layers;
- **6 Percolation Tanks** for promoting distributed infiltration;
- **5 Check Dams** for reducing runoff velocity and enhancing streambed infiltration; and
- **5 Bandharas** for controlling saline tidal ingress at coastal stream mouths.

The spatial distribution of these structures was linked to the hydrogeological characteristics of the island, with recharge shafts and percolation tanks concentrated mainly in favourable

western areas, check dams associated with suitable ephemeral drainage systems, and bandharas positioned at coastal stream mouths.

9.2.4 Water Demand, Availability and Stress Assessment (Chapter 7):

The assessment of sectoral water requirements demonstrated that total water demand increased from **290.97 MCM in 2001 to 291.27 MCM in 2021** and is projected to reach **292.65 MCM by 2041**. Agriculture accounts for more than **99% of the total demand**, highlighting the dominant influence of irrigation on the island's water requirement.

Post-monsoon water availability exhibited substantial interannual variability, ranging from approximately **1,256 MLY in dry years to more than 2,324 MLY in wet years**. This represents a difference of approximately **1,068 MLY** between dry and wet conditions.

The projected **Water Stress Index (WSI) for 2026–2030 ranged from 0.65 to 1.05**, with dry-year conditions reaching the critical stress category. Even under the wettest projected condition, the WSI remained approximately **0.66**, indicating that existing water resources provide limited surplus under the assessed conditions.

9.2.5 Integrated Water Resource Development Plan (Chapter 8)

The findings from the hydrogeological, modelling, MAR and water-demand assessments were synthesised into a **five-phase, 10-year Integrated Water Resource Development Plan for 2026–2035**. The plan progresses from institutional preparation and pilot interventions to coastal protection, expansion of MAR measures and long-term sustainability actions.

The major implementation components include:

- **Phase 1 – Awareness and Preparation:** community mobilisation, VWUA formation, monitoring expansion and baseline assessment;
- **Phase 2 – Pilot Interventions:** drip-irrigation implementation, pilot MAR structures and canal-lining measures;
- **Phase 3 – Coastal Protection:** implementation of bandharas and regulated groundwater abstraction;
- **Phase 4 – Scaling Up:** expansion to all **23 MAR structures**, palaeochannel exploration and wider adoption of efficient irrigation; and
- **Phase 5 – Long-Term Sustainability:** piloodi cultivation, restoration of traditional water systems and periodic review.

The plan targets a **27% reduction in total water demand**, including a **30% reduction in agricultural demand and 20% reduction in domestic demand**, together with an additional **60 MLY of water supply through MAR interventions**.

9.2.6 Overall Synthesis:

Collectively, the findings demonstrate that the freshwater system of Khadir Island is controlled by the interaction of **climatic, geological, recharge, abstraction, freshwater-lens, and seawater-intrusion processes**. Sustainable management therefore requires an integrated approach combining **groundwater assessment, recharge enhancement, abstraction management, salinity monitoring, water-use efficiency, and community participation**.

The **six research objectives stated in Chapter 1** were addressed through the integrated investigations undertaken in this study. **Table 9.1 summarises the corresponding objectives and achieved outcomes**.

Table 9.1: Comparison of Stated Research Objectives and Achieved Outcomes

Sr. No.	Stated Research Objective	Achieved Outcome
1	To characterise the geological, lithological, geomorphological, and hydrogeological framework of Khadir Island and the broader GRK island belt using remote sensing, GIS, and field surveys.	The geological, lithological, geomorphological and hydrogeological framework of Khadir Island was established through RS-GIS analysis, field investigations, well inventory, lithological observations and groundwater-quality assessment . The study identified distinct spatial variations in groundwater conditions, particularly between the western and eastern sectors of the island.
2	To delineate groundwater potential zones (GWPZ) and identify suitable sites for managed aquifer recharge (MAR) using the Multi-Influencing Factor (MIF) method integrated with RS-GIS.	An integrated RS-GIS-MIF approach using eight thematic layers was developed for groundwater potential zoning. The island was classified into Good (8.45%), Moderate (90.45%) and Poor (1.10%) zones . The assessment was further integrated with site-suitability criteria to identify 23 MAR locations comprising recharge shafts, percolation tanks, check dams and bandharas.

Sr. No.	Stated Research Objective	Achieved Outcome
3	To develop a transient groundwater flow model (MODFLOW-6) for Khadir Island, quantify the water budget through zone budget analysis, and assess the sustainability of current abstraction patterns.	A transient three-dimensional MODFLOW-6 model for 2001–2020 was developed using four hydrostratigraphic layers. The calibrated model achieved RMSE of 1.24 m, MAE of 0.98 m and mass-balance error below 0.5% . Zone-budget analysis quantified recharge, evapotranspiration, coastal outflow and pumping, providing a quantitative assessment of groundwater-system behaviour and abstraction pressure.
4	To simulate seawater intrusion dynamics using a density-dependent sharp-interface approach (MODFLOW-SWI2), validate the model with hydrochemical indicators, and identify critical management thresholds.	The SWI2 model quantified progressive inland movement of the saline front from 1.0 km in 2005 to 6.3 km in 2020 , with intrusion rates increasing from 0.20 to 0.48 km/year . A critical intrusion threshold of approximately 2.4 km was identified. Model results were independently supported by hydrochemical indicators including TDS, chloride and Na⁺/Cl⁻ ratios .
5	To quantify the temporal mismatch between water supply and sectoral demand (domestic, agricultural, livestock, tourism) as a basis for designing storage and demand-management interventions.	Sector-wise water demand and water availability were quantified for the major water-use sectors. Total demand increased from 290.97 MCM in 2001 to 291.27 MCM in 2021 and is projected to reach 292.65 MCM by 2041 . The analysis also demonstrated substantial interannual variability in water availability and WSI values of 0.65–1.05 for 2026–2030 , establishing the need for demand-management and storage interventions.

Sr. No.	Stated Research Objective	Achieved Outcome
6	To synthesise the findings into an integrated water resource development plan for the isolated islands of the Great Rann of Kachchh, addressing both hydrogeological and socio-economic dimensions.	The findings were integrated into a five-phase, 10-year Integrated Water Resource Development Plan (2026–2035) incorporating MAR, abstraction management, irrigation-efficiency measures, groundwater monitoring, coastal protection and community participation. The proposed framework targets a 27% reduction in total water demand and 60 MLY additional supply through MAR , providing a structured basis for sustainable water-resource management.

9.3 CONTRIBUTIONS TO SCIENTIFIC KNOWLEDGE

This study makes the following original contributions to the field of hydrogeology and water resource management:

1. **First systematic GWPZ mapping for Khadir Island:** Prior to this study, no RS-GIS-MIF groundwater potential assessment had been conducted for any of the isolated bays of the Great Rann of Kachchh. The GWPZ map provides a scientific basis for targeting wells and MAR structures in this data-scarce, hyper-saline environment.
2. **First integrated groundwater flow and seawater intrusion model for the GRK islands:** The MODFLOW-6 and SWI2 models, despite data limitations, quantify the water budget and intrusion dynamics, identifying a critical threshold at 2.4 km and the dominant control of recharge variability.
3. **Multi-line validation strategy for data-scarce conditions:** The combination of water balance closure, sensitivity analysis, hydrogeochemical validation (Na^+/Cl^- ratios, TDS trends), and parameter plausibility offers a replicable framework for establishing model credibility where monitoring networks are sparse.
4. **Quantification of seawater intrusion progression with future projection:** The study provides the first quantitative assessment of intrusion rates (0.20–0.48 km/yr) for Khadir Island, identifies an acceleration threshold at 2.4 km, and presents two-scenario projections to 2025 (7.95–9.60 km), establishing a baseline for management intervention.

5. **Comprehensive water demand and stress assessment (2001–2041):** The sectoral water demand analysis and Water Stress Index projections provide a quantitative understanding of the island's vulnerability to drought and climate variability.
6. **Integrated water resource development plan:** The five-phase, 10-year plan provides a practical, community-centred blueprint for Khadir Island that is transferable to other arid island aquifers globally. The plan integrates traditional knowledge with modern scientific approaches.

9.4 INTEGRATED MANAGEMENT STRATEGIES AND FUTURE PERSPECTIVES

This section presents the integrated management strategies and future perspectives derived from the hydrogeological investigations, groundwater modelling, seawater intrusion assessment, and water stress analysis conducted for Khadir Island. The proposed recommendations focus on sustainable groundwater management, seawater intrusion mitigation, recharge enhancement, policy-level interventions, and future research priorities required to ensure long-term freshwater security and climate resilience in the hyper-arid environment of the Great Rann of Kachchh.

9.4.1 Recommendations for Water Resource Management on Khadir Island

Immediate (Years 1–2):

1. Reduce abstraction by 30–40% through a combination of drip irrigation conversion (target: 80% of irrigated area), leak repair in the domestic network, and public awareness campaigns. The agricultural sector offers the largest potential savings.
2. Install 3 new monitoring wells along a transect from the coast to the central villages (at 2 km, 4 km, and 6 km from the coast) to track the saline front and provide early warning of further intrusion.
3. Form Village Water User Associations (VWUAs) in all ten villages, with elected representatives from pastoralist, farmer, artisan, and tourism sectors.
4. Construct 3 pilot check dams and 2 pilot recharge shafts (as identified in Chapter 6) to demonstrate the effectiveness of MAR and build community support.

Short-Term (Years 2–5):

5. Construct the 5 bandharas at the mouths of streams to block tidal ingress. This is the single most important structural intervention to halt further seawater intrusion.
6. Scale up drip irrigation to cover 80% of the irrigated area, increasing irrigation efficiency from 60% to 85%. Provide support through existing government schemes.
7. Line the most seepage-prone canal sections to reduce conveyance losses.

Medium-Term (Years 4–7):

8. Drill two deep exploratory boreholes (150–200 m) to investigate the palaeochannel aquifer potential. Conduct isotopic dating (^{14}C , ^{36}Cl) to determine water age and renewability.
9. Scale up piloodi (*Salvadora persica*) cultivation as a salt-tolerant cash crop. Establish market linkages for kardi oil.
10. Develop off-season tourism products to extend the tourist season beyond November–February, reducing seasonal water demand peaks.

Long-Term (Years 5–10, ongoing):

11. Conduct annual participatory reviews involving VWUAs, government agencies (CGWB, GWRDC, GWSSB), and researchers to assess progress, adjust abstraction caps, and plan for the following year.
12. Monitor Na^+/Cl^- ratios as an early warning indicator of seawater intrusion. Regular quarterly sampling of key wells in the Moderate zone provides a cost-effective early warning system.

9.4.2 Recommendations for Policy Makers

1. Integrate the Groundwater Potential Zone (GWPZ) map and proposed Managed Aquifer Recharge (MAR) interventions into the District Groundwater Management Plan for Kachchh under the Atal Bhujal Yojana. Priority should be given to the implementation of the 23 identified MAR structures to enhance groundwater recharge and improve freshwater availability.
2. Expand the groundwater monitoring network across all inhabited islands (bets) of the Great Rann of Kachchh, including Khadir, Bela, and Chorar. At present, long-term groundwater monitoring is limited to Khadir Island. A minimum of two dedicated monitoring wells should be established on each inhabited bet to facilitate systematic assessment of groundwater levels and quality.
3. Establish a groundwater abstraction monitoring system for irrigation wells throughout the Great Rann of Kachchh region. Periodic measurement and reporting of groundwater withdrawals are essential for sustainable resource management, improved water budgeting, and adaptive decision-making.
4. Promote the restoration and maintenance of traditional water-harvesting systems, including kunds, vavs, village ponds, and tanks, through convergence with MGNREGS

and related rural development programmes. These indigenous structures can effectively complement modern MAR interventions and enhance local water security.

5. Encourage nature-based solutions and climate-resilient land management practices, such as piloodi cultivation and ecosystem-based recharge enhancement measures, through support from the National Mission on Sustainable Agriculture (NMSA) and the National Adaptation Fund for Climate Change (NAFCC).
6. Undertake detailed hydrogeological investigations of the regional palaeochannel aquifer system extending across the northern Great Rann of Kachchh. The occurrence of artesian conditions in several locations suggests the possibility of a regionally connected groundwater system. Further scientific studies are required to evaluate its extent, recharge characteristics, groundwater quality, and sustainable development potential.

9.4.3 Recommendations for Future Research

Although the present study has developed an integrated geo-hydrological framework for groundwater assessment and sustainable water resource management on Khadir Island, several scientific and technical issues require further investigation. Future research should focus on reducing model uncertainty, improving the understanding of groundwater flow and seawater intrusion processes, strengthening long-term monitoring, and evaluating the impacts of climate variability and anthropogenic stresses. Such investigations will improve the reliability of groundwater management strategies and facilitate sustainable utilisation of groundwater resources in the Great Rann of Kachchh (GRK).

The major recommendations for future research are presented below.

1. Long-Term Groundwater Monitoring: A comprehensive groundwater monitoring network should be established by installing additional observation wells equipped with automated water-level recorders. Periodic monitoring of groundwater quality, including hydrogeochemical indicators such as Na^+/Cl^- ratio, chloride concentration, and total dissolved solids (TDS), should be undertaken to improve model calibration, validate long-term groundwater trends, and provide an early-warning system for seawater intrusion (Anderson et al., 2015; Werner et al., 2013).

2. Climate Change Impact Assessment: The calibrated MODFLOW-6 and SWI2 models may be extended to evaluate the effects of future climate change using CMIP6 or IPCC Sixth Assessment Report (AR6) climate scenarios. Assessment of rainfall variability, groundwater

recharge, drought frequency, and seawater intrusion under projected climate conditions would support the development of climate-resilient groundwater management strategies (IPCC, 2021).

3. Post-Implementation Evaluation of Managed Aquifer Recharge (MAR): Following the implementation of the proposed Managed Aquifer Recharge (MAR) structures, long-term field investigations should be carried out to evaluate recharge efficiency, groundwater level recovery, groundwater quality improvement, and the overall economic feasibility of MAR interventions. Such evaluations will provide valuable information for optimizing future recharge programmes under arid environmental conditions (Dillon et al., 2009).

4. Investigation of Deep Paleochannel Aquifers: Future investigations should include deep exploratory drilling, geophysical surveys, pumping tests, and environmental isotope analyses (^{14}C , ^{36}Cl , ^{18}O and ^2H) to determine the origin, residence time, and recharge history of groundwater stored within palaeochannel aquifers. Identification of fossil groundwater resources would assist in distinguishing renewable and non-renewable groundwater reserves and support long-term groundwater planning (Clark and Fritz, 1997; IAEA, 2013).

5. Advanced Variable-Density Groundwater Modelling

The present study employed the SWI2 package based on the sharp-interface approach for simulating seawater intrusion. Future studies may adopt fully coupled variable-density groundwater flow and solute transport models, such as SEAWAT or equivalent transport models, to simulate the freshwater–saltwater transition zone and improve prediction of groundwater salinity distributions (Langevin et al., 2008; Werner et al., 2013).

6. Integrated Socio-Hydrological Modelling

Future research should integrate groundwater models with socio-economic and behavioural components to evaluate the influence of irrigation practices, groundwater abstraction, cropping patterns, and policy interventions on groundwater sustainability. Such integrated socio-hydrological models would facilitate adaptive groundwater management under changing environmental and socio-economic conditions (Sivapalan et al., 2012).

7. Regional Application of the Integrated Framework

The integrated RS–GIS–MIF–MODFLOW-6–SWI2 framework developed in the present study may be extended to other islands (bets) of the Great Rann of Kachchh, including Bela Island and Chorar Island, after incorporating site-specific geological and hydrogeological

characteristics. Comparative regional investigations would contribute to integrated groundwater resource planning across the entire GRK region.

8. UAV-Based Environmental Monitoring: Future investigations may utilise unmanned aerial vehicles (UAVs) equipped with thermal and multispectral sensors to generate high-resolution datasets on evapotranspiration, vegetation health, soil moisture, and recharge conditions. Integration of UAV observations with satellite remote sensing would improve groundwater recharge estimation and environmental monitoring (Anderson and Gaston, 2013).

To facilitate systematic implementation of the above recommendations, a research roadmap outlining priority areas, key activities, and indicative implementation timelines is presented in **Table 9.2**.

Table 9.2: Research Roadmap for Future Investigations in Khadir Island

Priority	Research Area	Key Activities	Expected Timeline
High	Long-term groundwater monitoring	Establish 3–5 additional monitoring wells, install automated water-level loggers, and conduct quarterly groundwater quality and hydrogeochemical monitoring	1–3 years
High	Climate change impact assessment	Downscale CMIP6/IPCC AR6 climate projections, evaluate recharge variability, and simulate groundwater response using MODFLOW-6–SWI2	2–4 years
High	Post-implementation evaluation of MAR structures	Monitor recharge efficiency, groundwater level recovery, groundwater quality improvement, and undertake cost–benefit assessment of implemented MAR structures	2–5 years
High	Palaeochannel investigation	Conduct deep exploratory drilling, geophysical surveys, environmental isotope analysis (^{14}C , ^{36}Cl , ^{18}O and ^2H), and aquifer performance testing	2–4 years

Priority	Research Area	Key Activities	Expected Timeline
Medium	Variable-density groundwater modelling	Acquire salinity profile data, undertake Electrical Resistivity Tomography (ERT) surveys, and develop SEAWAT or equivalent variable-density transport models	3–5 years
Medium	Integrated socio-hydrological modelling	Develop coupled groundwater–human interaction models incorporating irrigation practices, groundwater abstraction, and policy interventions	3–5 years
Medium	Regional application of the integrated framework	Apply the RS–GIS–MIF–MODFLOW-6–SWI2 framework to Bela Island, Chorar Island, and other islands of the Great Rann of Kachchh	3–5 years
Low	UAV-based environmental monitoring	Conduct high-resolution thermal and multispectral UAV surveys for evapotranspiration, vegetation stress, and soil moisture assessment	1–2 years

Source: Prepared based on the findings of the present study and recommendations from Anderson et al. (2015), Dillon et al. (2009), Werner et al. (2013), IPCC (2021), IAEA (2013), and Sivapalan et al. (2012).

9.5 CONCLUDING REMARKS

The Great Rann of Kachchh represents one of the most hydrogeologically fragile and water-stressed regions of India, where sustainable groundwater management is constrained by arid climatic conditions, highly variable rainfall, saline surroundings, and limited freshwater resources. Among its isolated islands, Khadir Island possesses exceptional environmental, archaeological, and socio-economic significance. From the remarkable water-management systems of the Harappan civilisation at Dholavira to the present day, the island has continuously relied on effective water-resource management for its survival and development.

The present investigation demonstrates that groundwater resources on Khadir Island are under increasing stress due to the combined influence of limited natural recharge,

groundwater abstraction, agricultural expansion, increasing domestic and tourism demands, and progressive seawater intrusion. The calibrated MODFLOW-6 and SWI2 simulations indicate progressive inland migration of the freshwater–saltwater interface under the assessed groundwater-development conditions, while the water-demand analysis indicates that future requirements may exceed sustainable groundwater availability without appropriate management interventions.

To address these challenges, the present research developed a comprehensive **Integrated Geo-Hydrological Framework** for groundwater assessment and sustainable water-resource management. The framework integrates Remote Sensing, Geographic Information System (GIS), Multi-Influencing Factor (MIF) analysis, hydrogeological investigations, numerical groundwater-flow modelling using MODFLOW-6, seawater-intrusion simulation using SWI2, hydrogeochemical investigations, groundwater budgeting, water-demand assessment, and water-stress analysis into a unified decision-support framework.

The major scientific contributions of this study include the delineation of groundwater-potential zones, development and calibration of a groundwater-flow model, simulation of seawater intrusion, hydrogeochemical validation of groundwater salinisation processes, assessment of groundwater availability and sector-wise water demand, identification and prioritisation of suitable Managed Aquifer Recharge (MAR) sites, and formulation of a phased **Integrated Water Resource Development Plan** for Khadir Island. Collectively, these components establish an integrated scientific basis for groundwater management under data-scarce arid island conditions.

The proposed management strategy, comprising **Managed Aquifer Recharge (MAR), groundwater-abstraction control, continuous groundwater monitoring, irrigation water-use efficiency, hydrochemical surveillance, and community participation through Village Water User Associations (VWUAs)**, provides a practical pathway for improving long-term groundwater sustainability. The uncertainty and sensitivity assessment undertaken in the study further indicates that the principal hydrogeological interpretations and management implications provide a useful basis for regional-scale planning, while continued monitoring remains essential for refining future decisions.

Future climate variability represents an important consideration for the long-term effectiveness of the proposed management strategy. Changes in rainfall patterns,

effective recharge, temperature, potential evapotranspiration, sea level, and sectoral water demand may alter the groundwater balance and freshwater-lens stability of Khadir Island. Reduced effective monsoon recharge could decrease freshwater replenishment, while higher temperatures and increased water demand could intensify groundwater stress. Similarly, sea-level rise and associated changes in saline hydraulic conditions could increase the vulnerability of the freshwater lens to seawater intrusion. The accelerated scenario assessed in this study therefore provides an important indication of potential future risk rather than a definitive prediction. Conversely, effective capture of available monsoon runoff through the proposed MAR network could enhance recharge and partially offset these pressures. These considerations highlight the importance of incorporating future climate scenarios into subsequent modelling studies and of adopting adaptive abstraction limits, long-term monitoring, and periodic revision of management measures.

Beyond Khadir Island, the integrated **RS–GIS–MIF–MODFLOW-6–SWI2 framework** developed in this research offers a transferable methodology for groundwater assessment and management in other islands of the Great Rann of Kachchh and comparable arid coastal environments experiencing groundwater depletion and seawater intrusion. With appropriate adjustment to local hydrogeological and socio-economic conditions, the framework can support sustainable groundwater planning in environmentally sensitive island and coastal aquifer systems.

Although the hydrogeological challenges confronting Khadir Island are substantial, they can be addressed through continued scientific investigation, long-term groundwater monitoring, adaptive management, effective policy implementation, and active community participation. The remarkable water-management achievements of the Harappan civilisation at Dholavira demonstrate that sustainable water management in this harsh environment has been possible for thousands of years. Building upon this enduring legacy, the present research provides a modern scientific foundation for integrated groundwater-resource management and contributes towards strengthening long-term water security for Khadir Island and the broader Great Rann of Kachchh.

LOOKING AHEAD

From Challenge to Sustainable Future



“

The challenges are formidable, **but they are not impossible.** With committed **policy support**, active **community participation**, and **continued research**, **Khadir Island** can transition from **crisis to sustainability** — and serve as a **model** for other water-stressed arid islands around the world.

”



PROTECT
Freshwater Resources



PRACTICE
Sustainable Solutions



INVOLVE
Communities in Water Stewardship



INVEST
in Science & Innovation



INSPIRE
Global Action, Local Impact



TOGETHER, WE CAN SECURE WATER • SUSTAIN LIFE • BUILD RESILIENT FUTURES



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2. Integrated Water Balance and Water Stress Index–Based Sustainability Assessment of a Semi-Arid Island Ecosystem by Sagar Vinodray Nimavat and Dr. Mahendrasinh S. Gadhavi in *Journal of Water Pollution & Purification Research*, Vol. 13, Issue 01, 2026, ISSN No.: 2394-7306, DOI: <https://doi.org/10.37591/JoWPPR.v13i01.238470>.
3. Buried Rivers, Thirsty Island Belt: A Review of Water Challenges in the Great Rann of Kachchh by Sagar Vinodray Nimavat and Dr. Mahendrasinh S. Gadhavi in *International Journal of Environmental Chemistry*, Vol. 12, Issue 01, 2026, ISSN No.: 2456-5245, DOI: <https://doi.org/10.37628/ijec.v12i01.24655>.

APPENDIX: FIELD VISIT PHOTOGRAPH



FIELD VISIT – 2021

KHADIR ISLAND, GREAT RANN OF KACHCHH, GUJARAT



POND / SURFACE WATER BODY ON KHADIR ISLAND



WATER QUALITY TESTING IN FIELD



WATER QUALITY MEASUREMENT ON SITE



WATER TESTING KIT USED IN FIELD



SALINE / WATERLOGGED LAND AREA



FIELD OBSERVATIONS AT SITE

FIELD VISIT 2021

FIELD VISIT – 2021

KHADIR ISLAND, GREAT RANN OF KACHCHH, GUJARAT



WATER OBSERVATION AT POND



NATURALLY WEATHERED ROCK FORMATION



EXCAVATED STRUCTURE / STAIRCASE



VIEW OF THE HERITAGE MOUND / SITE EXTENT



VIEW OF THE GREAT RANN – KUTCHH



HERITAGE-STYLE ACCOMMODATION AT SITE

FIELD VISIT 2021
