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Integrated Water Balance and Water Stress Index–Based Sustainability Assessment of a Semi-Arid Island Ecosystem

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Abstract

Freshwater scarcity is an increasingly critical challenge in semi-arid island environments due to limited natural water availability, high dependence on seasonal rainfall, growing population pressure, and expanding agricultural activities. Island ecosystems are particularly vulnerable to water stress because they often lack perennial surface water sources and rely heavily on groundwater recharge during short and highly variable monsoon periods. This study presents a comprehensive assessment of water demand, post-monsoon water availability, and water stress for Khadir Island, India, using a Water Stress Index (WSI)–based sustainability framework. Sector-wise water demand for domestic, livestock, and agricultural uses was estimated using population statistics, livestock census data, and crop water requirement analysis. Post-monsoon water availability was evaluated based on rainfall records, groundwater recharge estimates, and storage characteristics. Future water availability for the period 2022–2025 was projected using rainfall-based scenarios representing wet, normal, and dry conditions. The Water Stress Index was computed as the ratio of total water demand to available water to assess sustainability and vulnerability. Results indicate that total annual water demand increased from 1,207.5 million litres per year (MLY) in 2011 to a projected 1,369.6 MLY by 2025, primarily driven by population growth and agricultural water use. Agriculture accounted for more than 75% of total water demand. Post-monsoon water availability exhibited strong interannual variability, ranging from approximately 1,350 MLY during dry years to over 2,300 MLY during wet years. WSI values ranged between 0.62 and 1.00, indicating moderate to high water stress. The study demonstrates that a WSI-based approach provides a practical, multidisciplinary, and policy-relevant tool for sustainable water planning in semi-arid island regions.

Keywords: Water balance, water stress index, island sustainability, agricultural water demand, groundwater recharge, climate variability, water policy

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INTRODUCTION

Water scarcity has emerged as one of the most pressing challenges affecting sustainable development across the globe. Rapid population growth, agricultural intensification, climate variability, and excessive groundwater abstraction have significantly increased pressure on limited freshwater resources (1). Semi-arid and arid regions are particularly vulnerable due to low and highly variable rainfall, high evapotranspiration, and increasing competition among water-use sectors.

Island ecosystems represent a unique and highly sensitive category within water-scarce regions. Unlike continental systems, islands often lack perennial surface water sources and depend predominantly on groundwater recharge from short monsoon periods (2). Recent climate assessments highlight that groundwater-dependent regions are among the most vulnerable to climate change impacts, especially due to reductions in recharge and increased drought frequency (3).

Integrated water resource assessment approaches are increasingly recognized as essential for understanding water scarcity and supporting sustainable decision-making (4). Among various indicators, the Water Stress Index (WSI), defined as the ratio of water demand to water availability, has been widely applied to assess water scarcity and sustainability at global, regional, and basin scales (5). More recent studies emphasize the usefulness of WSI for policy-oriented water governance due to its simplicity, transparency, and ease of interpretation (6).

Khadir Island, located in a semi-arid region of western India, represents a typical island system where domestic water supply, livestock needs, and agricultural irrigation compete for limited groundwater resources. Agriculture is the primary livelihood activity, making water availability a critical socio-economic concern. Despite this, comprehensive island-scale studies integrating water demand, post-monsoon availability, future rainfall scenarios, and sustainability indicators remain limited.

The objectives of this study are to:
(a) Estimate sector-wise water demand for domestic, livestock, and agricultural uses;
(b) Assess post-monsoon water availability based on rainfall and groundwater recharge;
(c) Project future water availability using rainfall-based scenarios;
(d) Compute the Water Stress Index for present and future periods; and
(e) Develop a WSI-based sustainability and policy framework applicable to semi-arid island environments.

STUDY AREA

Khadir Island covers a total geographical area of approximately 31,405 ha and is located in a semi-arid climatic region. The climate is characterized by high temperatures, low mean annual rainfall, and strong interannual variability in monsoon precipitation (7). Rainfall is concentrated within a short monsoon period, while the remaining months experience prolonged dry conditions.

Agriculture occupies approximately 14,132 ha of the island and follows a seasonal cropping pattern comprising Kharif, Rabi, and summer seasons. Groundwater is the primary source of water for domestic supply, livestock, and irrigation (Figure 1). The aquifers underlying the island are shallow and have limited storage capacity, making groundwater availability highly sensitive to recharge variability and over-extraction (8).

DATA AND METHODOLOGY

Methodological Framework

The methodological framework integrates water demand estimation, post-monsoon water availability assessment, future scenario analysis, and Water Stress Index computation. The approach follows a step-by-step workflow linking data inputs, analytical procedures, and sustainability interpretation, making it suitable for multidisciplinary and policy-oriented applications (9) (Figure 2).

Domestic Water Demand

Domestic water demand was estimated using village-level population data for 2011 and 2021. A per capita water supply norm of 135 litres per capita per day was applied, following national guidelines (10). Annual domestic water demand was calculated in million litres per year (MLY). Population projections for 2022–2025 were derived using observed growth trends (Table 1).

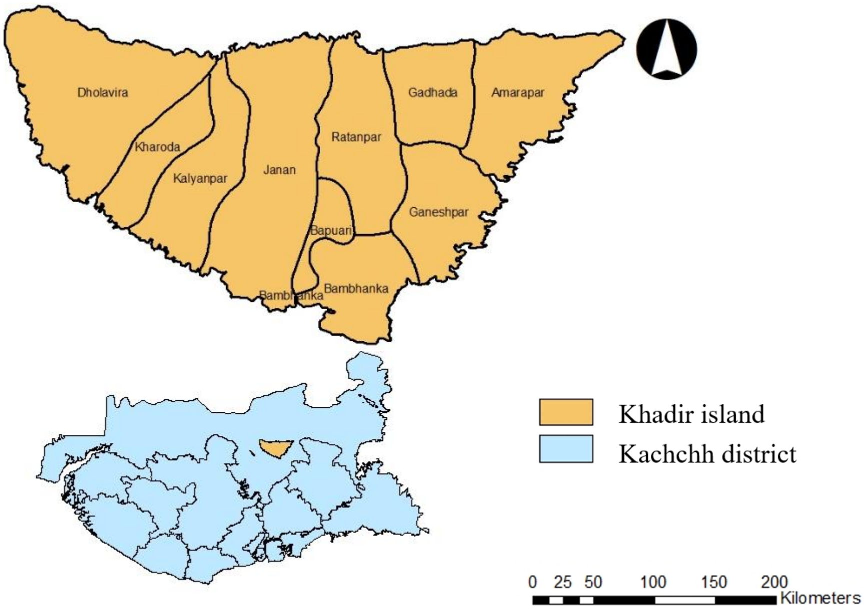

Figure 1. Location map of Khadir Island and administrative villages placement.

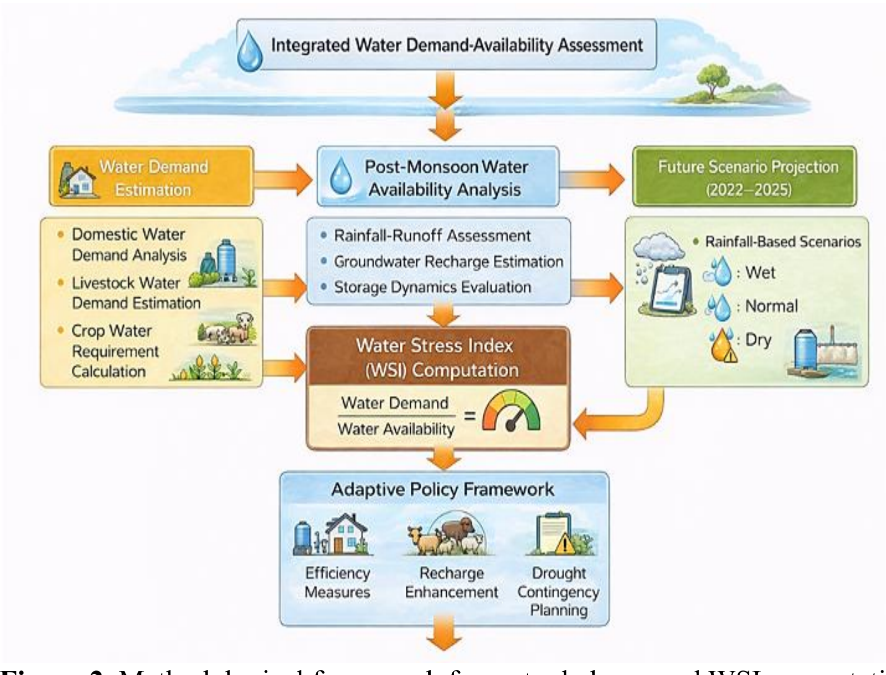

Figure 2. Methodological framework for water balance and WSI computation
(Flowchart: Demand → Availability → WSI → Policy Actions)

Livestock Water Demand

Livestock water demand was estimated using livestock population data for cattle, buffalo, sheep, and goats. Species-specific daily water requirement norms were applied (11). Due to the absence of updated census data, livestock population was assumed constant during the study period (12) (Table 2).

Agricultural Water Demand

Agricultural water demand was estimated using crop water requirement analysis based on net irrigation depth (13) (Figure 3). Seasonal crop water requirements were calculated for Kharif, Rabi, and summer seasons, resulting in a total annual crop water requirement of 163 cm. This approach is consistent with recent irrigation planning studies in semi-arid regions (14) (Table 3).

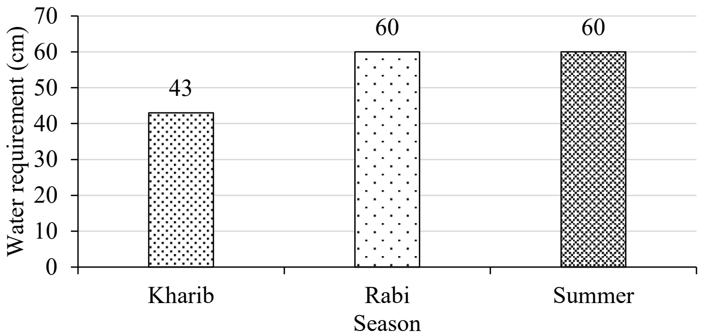

Figure 3. Seasonal distribution of crop water requirement

Table 1. Village-wise human population and domestic water requirement (2011–2021).

S.No.	Village	Area (ha)	Population 2011	Population 2021	Houses	Water Requirement (LPCD)	Human Water Demand (MLD)
1	Dholavira	5287.43	2222	2555	422	135	0.345
2	Kharoda	1993.91	388	446	69	135	0.06
3	Kalyanpar	1895.68	1363	1567	276	135	0.212
4	Janan	5431.62	1043	1199	234	135	0.162
5	Ratanpar	5384.44	989	1137	203	135	0.154
6	Gadhada	2795.03	5281	6073	118	135	0.82
7	Amarapar	3723.01	1747	2009	398	135	0.271
8	Ganeshpar	2723.68	1144	1316	239	135	0.178
9	Bambhanka	2170.39	829	953	154	135	0.129
Total	-	31405.2	15006	17257	2113	-	2.33

Table 2. Village-wise livestock population and livestock water requirement.

S. No.	Village	Cows	Buffalo	Sheep	Goats	Horses/ Ponies	Total Livestock	Livestock Water Demand (MLD)
1	Dholavira	1140	786	275	863	0	3064	0.147
2	Kharoda	143	87	137	1030	0	1397	0.032
3	Kalyanpar	871	496	177	456	0	2000	0.102
4	Janan	102	250	300	69	0	721	0.029
5	Ratanpar	160	498	1153	443	0	2254	0.067
6	Gadhada	179	77	1179	327	0	1762	0.038
7	Amarapar	699	688	190	574	0	2151	0.105
8	Ganeshpar	311	598	187	146	0	1242	0.067
9	Bambhanka	271	504	322	577	0	1674	0.065
Total		3876	3984	3920	4485	0	16265	0.651

Post-Monsoon Water Availability

Post-monsoon water availability was assessed by integrating effective rainfall contribution, groundwater recharge, and groundwater storage characteristics. Groundwater recharge was estimated using pre- and post-monsoon groundwater level fluctuations following CGWB (2017) guidelines. Dead storage was considered as the non-extractable portion of groundwater (15).

Future Water Availability Scenarios

Future water availability for 2022–2025 was projected using rainfall-based scenarios representing wet, normal, and dry years. Scenario-based approaches are recommended for water resource planning under climatic uncertainty (16).

Table 3. Season-wise crop water requirement for Khadir island (kharif, rabi, and summer crops with water depth in cm).

S.No.	Season	Crop Category (Representative)	Water Requirement (cm)	Agricultural Area (ha)	Water Volume (m³)	Water Demand (MLY)	Remarks
1	Kharif	Bajra / Vegetables / Fodder / Fruits	43	14132.3	60769062	60.77	Kharif season consumes ~60% of agricultural water
2	Rabi	Vegetables / Fodder / Fruits	60	14132.3	84794040	84.79	Irrigated cropping with soil amelioration
3	Summer	Vegetables / Fodder / Fruits	60	14132.3	84794040	84.79	High evapotranspiration, irrigation dependent
					Total Annual Agricultural Demand	230.36 MLY	

Table 4. Annual total water requirement of khadir island (2011–2021).
(Human + Livestock + Agriculture)

Year	Population	Livestock	Human Demand (MLD)	Livestock Demand (MLD)	Agriculture Demand (MLY)	Total Water Requirement (MLY)
2011	15006	16265	2.03	0.651	230.36	1207.5
2015	15906	16265	2.15	0.651	230.36	1251.85
2020	17031	16265	2.3	0.651	230.36	1307.28
2021	17257	16265	2.33	0.651	230.36	1318.42

Table 5. Projected total water requirement of Khadir Island (2022–2025).
(Baseline demand projection)

Year	Population	Total Water Requirement (MLY)
2022	17508	1330.98
2023	17763	1343.67
2024	18021	1356.55
2025	18283	1369.64

Water Stress Index

The Water Stress Index (WSI) was calculated as the ratio of total annual water demand to total post-monsoon water availability (17). WSI values were classified into sustainability categories to support policy interpretation.

RESULTS

Water Demand Trends

Total water demand increased from 1,207.5 MLY in 2011 to 1,318.4 MLY in 2021 and is projected to reach 1,369.6 MLY by 2025 (Table 4 & 5). Agriculture accounted for more than 75% of total demand, followed by domestic and livestock uses (18).

Post-Monsoon Water Availability

Post-monsoon water availability exhibited strong interannual variability, ranging from approximately 1,350 MLY in dry years to over 2,300 MLY in wet years (Table 6). Groundwater recharge constituted the dominant component of available water, consistent with island hydrogeological studies (19).

Water Stress Index Results

WSI values ranged from 0.62 to 1.00 for the period 2022–2025 (Table 7 & 8). Moderate water stress conditions prevailed during normal and wet years, while dry years approached high stress thresholds, indicating vulnerability to drought (20) (Figure 4 & 5).

Table 6. Post-monsoon water availability of Khadir Island (2011–2021).
(Rainfall, recharge, groundwater storage, total availability)

Year	Rainfall (mm)	Recharge (ML)	Dead Storage (ML)	Total Water Available (MLY)
2011	932	1099.18	1224.8	2323.98
2013	507	942.16	1202.82	2144.97
2015	684	1067.78	1138.44	2206.21
2018	103	345.46	1012.82	1358.27
2020	282	628.1	1209.1	1837.2

Table 7. Projected post-monsoon water availability under rainfall scenarios (2022–2025).
(Wet, normal, and dry year scenarios)

Year	Scenario	Rainfall (mm)	Total Water Available (MLY)
2022	Normal	400	1650
2023	Wet	650	2170
2024	Dry	200	1350
2025	Normal	420	1720

Table 8. Water stress index (WSI) for Khadir Island (2022–2025).
(Availability, demand, WSI, stress category)

Year	Water Demand (MLY)	Water Availability (MLY)	WSI	Stress Category
2022	1330.98	1650	0.81	Moderate
2023	1343.67	2170	0.62	Moderate
2024	1356.55	1350	1	High
2025	1369.64	1720	0.8	Moderate

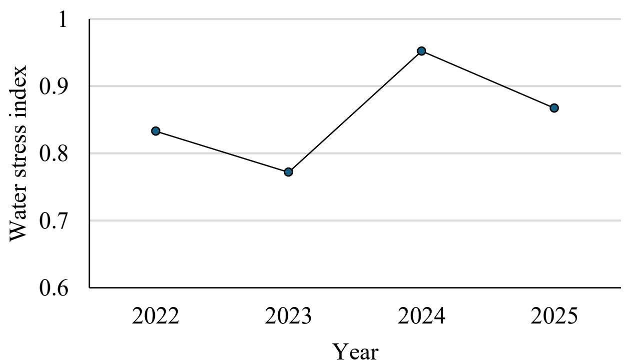

Figure 4. Water Stress Index (WSI) Trend for Khadir Island (2022–2025).

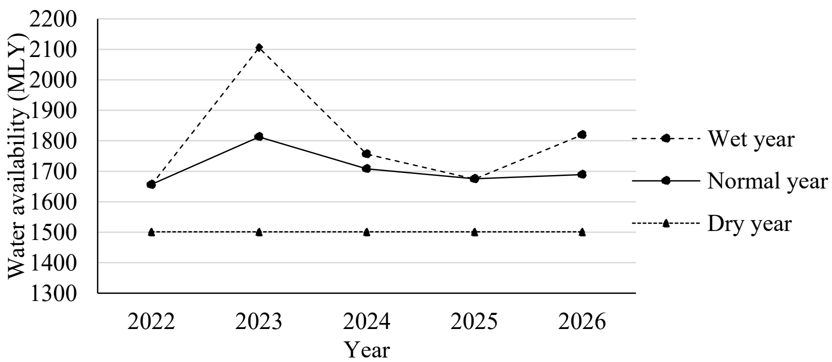

Figure 5. Projected water availability under rainfall scenarios (2022–2025).

DISCUSSION

The dominance of agricultural water demand indicates that irrigation efficiency improvements and crop diversification offer significant potential for reducing water stress. Even modest reductions in irrigation demand could substantially improve the island's water balance. The strong dependence of water availability on rainfall highlights the vulnerability of groundwater-dependent island systems to climate variability and change (21).

Compared to complex hydrological models, the WSI provides a simple yet effective indicator that can be easily communicated to planners and policymakers (22). Its integration with scenario analysis enhances its applicability for adaptive water management in data-limited environments (Figure 6).

SUSTAINABILITY AND POLICY IMPLICATIONS

A WSI-based sustainability framework allows water management actions to be aligned with observed and projected water stress levels. Under moderate stress conditions, emphasis should be placed on improving irrigation efficiency, promoting water-saving technologies, and enhancing groundwater recharge (Table 9) (12). During high stress conditions, stricter demand regulation, crop diversification, and drought preparedness become essential (Figure 7) (23).

CONCLUSIONS

This study presents a comprehensive assessment of water demand, post-monsoon water availability, and water stress for a semi-arid island ecosystem. Results indicate that Khadir Island experiences moderate to high water stress, driven primarily by agricultural water demand and rainfall variability. The Water Stress Index provides a practical, multidisciplinary, and policy-relevant tool for sustainable water management. The framework developed in this study is transferable to other semi-arid island and rural regions facing similar water challenges.

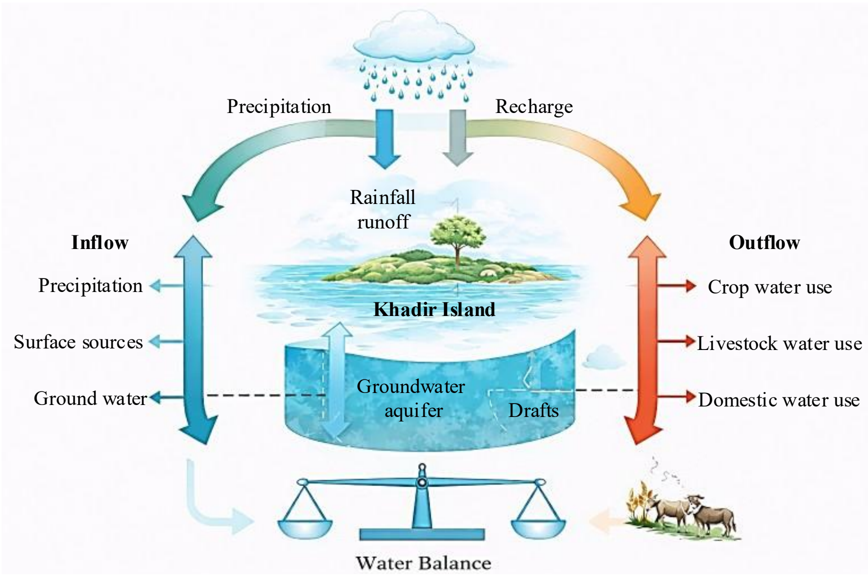

Figure 6. Water balance diagram of Khadir Island (Supply vs Demand schematic)

Table 9. WSI-based sustainability thresholds and policy responses.

S. No	WSI Range	Stress Level	Policy Action
1	< 0.60	Low	Normal operations
2	0.60–0.80	Moderate	Efficiency improvements
3	0.80–1.00	Vulnerable	Demand regulation
4	≥ 1.00	High	Emergency measures

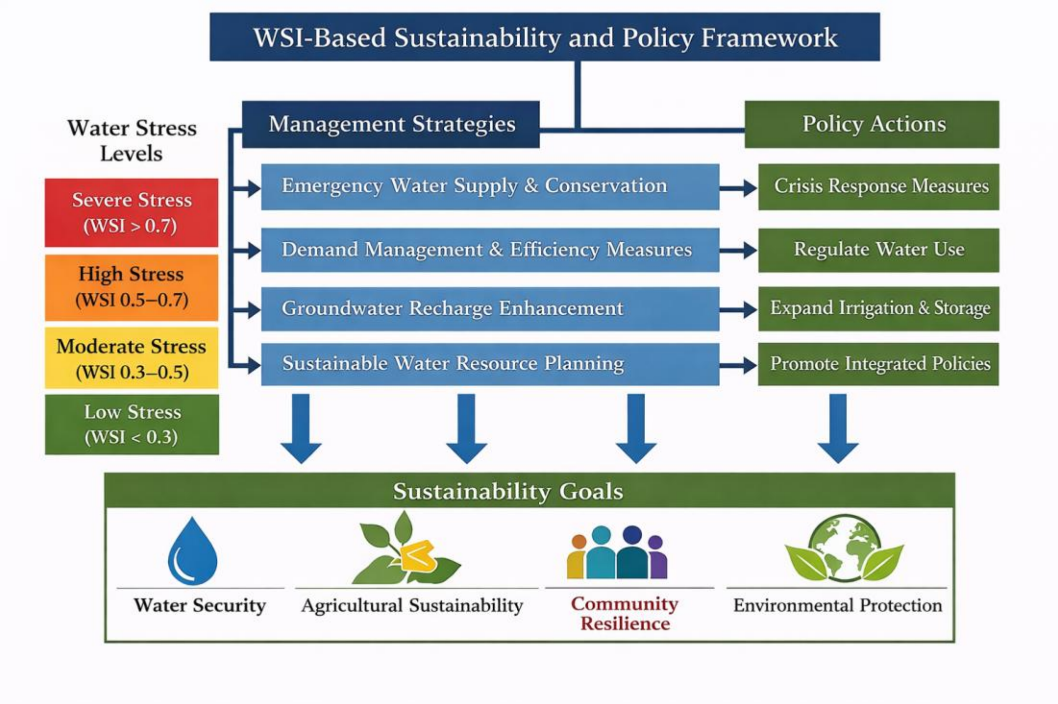

Figure 7. Conceptual framework linking WSI to adaptive policy actions.
(WSI → Sustainability → Policy interventions)

Declarations

Funding

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability

All data used in this study are presented within the manuscript.

Ethical Approval

Not applicable.

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