Assessing the Efficacy and Climate Resilience of Traditional Water Harvesting Systems in Jodhpur District, Rajasthan: A Geospatial and Hydrological Modeling Approach

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Abstract

Traditional Water Harvesting Systems (TWHS) are critical for water security in arid regions like Jodhpur district, Rajasthan, India, yet their contemporary efficacy and climate resilience remain inadequately quantified. This study comprehensively assesses selected TWHS, primarily nadis and johads, by integrating geospatial analysis for inventory and characterization, hydrological modeling (SCS-CN and water balance) for performance evaluation, CMIP6 climate change projections (SSP2-4.5 and SSP5-8.5) for resilience assessment, and multi-criteria decision analysis (MCDA) for identifying optimal scalability potential. Geospatial mapping identified 450 TWHS (280 nadis, 120 tankas, and 50 johad-like structures) across the Jodhpur district. Detailed characterization of 50 sample structures revealed significant variability in their storage capacities (mean nadi capacity: 18,500 m^3 ± 9,200 m^3) and catchment characteristics. Hydrological modeling under baseline conditions (1991-2020) indicated that an average nadi captured approximately 65% of its catchment runoff, providing crucial water resources for 4-5 months post-monsoon and enhancing localized groundwater recharge by an estimated 180 mm/year compared to non-TWHS areas. However, climate change projections for mid-century (2041-2070) predict a potential decrease in average annual inflow to TWHS by 8-18% and a reduction in water availability duration by 3-5 weeks, underscoring their vulnerability. Despite these challenges, GIS-MCDA identified that approximately 18% of the district's non-urban area is 'highly suitable' for new TWHS interventions, suggesting substantial scalability potential to harvest an additional 12-15 Million Cubic Meters (MCM) of rainwater annually. This research underscores the enduring hydrological importance of TWHS but emphasizes the urgent necessity for climate-resilient revival, adaptive management strategies, and strategic upscaling, informed by robust scientific assessments and active community participation, to bolster water security and enhance adaptive capacity in arid environments. Policy recommendations focus

on integrating TWHS into mainstream water resource planning, promoting climate-smart rehabilitation, and strengthening local institutional frameworks for sustainable TWHS governance.

Keywords: Traditional Water Harvesting, Rajasthan, Jodhpur, Geospatial Analysis, Hydrological Modeling, Climate Change Resilience, Water Scarcity, Sustainable Water Management, Arid Environments, Indigenous Knowledge, CMIP6

1. Introduction

Global water security is increasingly threatened by a confluence of factors including anthropogenic climate change, relentless population growth, and pervasive unsustainable resource management practices. Arid and semi-arid regions (ASARs), which constitute a significant portion of the Earth's terrestrial surface, are particularly vulnerable to these pressures, often teetering on the brink of acute water crises. Rajasthan, India, a predominantly arid state, faces a profound water deficit, possessing less than 1.2% of the nation's total water resources while concurrently supporting a substantial share of its human and livestock populations.

The Jodhpur district, located in the Thar Desert region of western Rajasthan, covering a geographical area of approximately 22,850 km^2, exemplifies these challenges. This region is characterized by exceedingly low and notoriously erratic monsoon rainfall, typically averaging between 300-350 mm annually, coupled with exceptionally high rates of evapotranspiration and alarming levels of groundwater depletion due to over-extraction for agriculture and domestic needs. The district's arid classification is well-established, and it forms a significant part of the Thar Desert. This precarious hydro-climatic vulnerability translates into frequent crop failures, significantly diminished livestock productivity, and pervasive socio-economic distress for its predominantly rural population, often compelling communities towards maladaptive coping strategies such as distress-induced migration or unsustainable reliance on expensive water tankers. The challenges faced by Jodhpur are representative of many ASARs globally, suggesting that findings and methodologies from this region could offer valuable lessons for other water-stressed areas. This context elevates the significance of the study's findings regarding TWHS efficacy and resilience, positioning the research as a potential blueprint for water management and climate adaptation strategies in similar arid zones worldwide.

In this historically water-stressed environment, Traditional Water Harvesting Systems (TWHS) have been the cornerstone of human survival and community resilience for millennia. Ingenious structures such as *nadis* (community village ponds), *johads* (earthen check dams), *tankas* (covered underground cisterns), and *beris* (shallow percolation wells) represent a rich legacy of accumulated indigenous knowledge and adaptive engineering, meticulously designed to capture and conserve scarce rainwater. These systems have traditionally been instrumental in supporting essential drinking water needs, enabling supplemental irrigation, and sustaining livestock, thereby forming the backbone of local water management and rural livelihoods.

However, the operational efficacy and long-term sustainability of many of these invaluable TWHS have witnessed a significant decline in recent decades. This deterioration can be attributed to a complex interplay of factors, including rapid shifts in land use patterns, profound socio-economic transformations (such as changing occupational structures and a decline in collective action), the widespread adoption of deep borewell technology for groundwater abstraction, and a concomitant weakening of traditional community-based management institutions. The shift towards borewells, for instance, represents a technological change that, while offering immediate water access, has contributed to both groundwater depletion and a reduced community focus on maintaining surface water harvesting structures. This indicates that the challenges facing TWHS are not merely technical but are deeply embedded in evolving socio-technical landscapes.

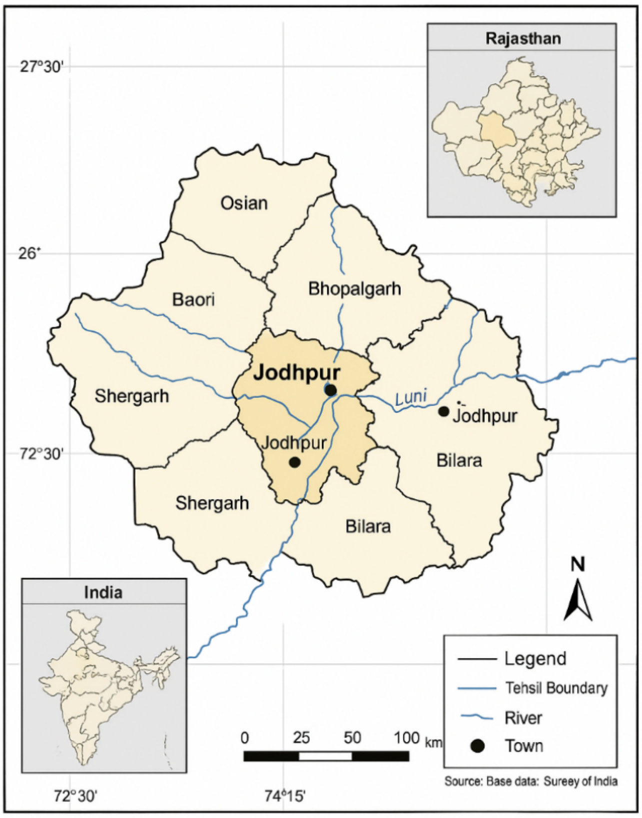


Figure 1: Study Area – Jodhpur District, Rajasthan, India, showing Administrative Divisions and Major Drainage. This map provides the geographical context for the study, delineating Jodhpur District within Rajasthan and India. It highlights the district's administrative tehsils and the primary ephemeral drainage system, including the Luni River.

The contemporary relevance of TWHS, particularly their potential role in climate change adaptation strategies and their integration into holistic water resource management frameworks, underscores the urgent need for a rigorous scientific assessment of their current performance and future potential. Modern analytical tools, including advanced remote sensing (RS) techniques, sophisticated Geographic Information Systems (GIS), and robust hydrological modeling, offer powerful capabilities to evaluate these decentralized systems quantitatively and spatially. Such scientifically grounded assessments are crucial for informing evidence-based strategies for their revival, optimizing their siting for maximum impact, and ensuring their effective integration into broader regional and national water security plans.

This research aims to comprehensively assess the hydrological efficacy, climate resilience, and scalability potential of selected TWHS (primarily *nadis* and *johads*, given their prevalence and community importance) within the Jodhpur district of Rajasthan. The specific objectives guiding this investigation are:

- To meticulously map the spatial distribution and characterize the key biophysical attributes (e.g., size, capacity, catchment characteristics) of existing TWHS across the Jodhpur district using an integrated suite of geospatial techniques.

- To develop, calibrate, and apply appropriate hydrological models to simulate the intricate water balance components (including runoff generation, surface storage dynamics, evaporation losses, and potential groundwater recharge) of representative TWHS under current baseline climatic conditions.
- To critically evaluate the potential impacts of a range of projected climate change scenarios (derived from CMIP6 GCMs) on the future hydrological performance, operational reliability, and overall water provisioning capacity of these TWHS.
- To identify and delineate optimal geographical locations for the strategic implementation of new TWHS interventions and for the targeted rehabilitation of existing, underperforming structures, utilizing GIS-based multi-criteria decision analysis (MCDA).
- To synthesize the research findings into a set of actionable, evidence-based recommendations designed to enhance the role of TWHS in promoting sustainable water management practices and strengthening climate adaptation strategies within the region.

This study distinguishes itself by employing an integrated approach that combines detailed hydrological modeling of TWHS efficacy with an ensemble of CMIP6 climate projections to assess their future resilience, and a spatially explicit MCDA for scalability analysis within the Jodhpur district. This combination is crucial for developing targeted and resilient water management solutions in one of India's most water-stressed arid zones. The findings are expected to contribute to enhancing water security, supporting resilient livelihoods, and promoting sustainable development in water-scarce arid environments like Jodhpur, aligning with national and global goals for water resource management and climate action.

2. Literature Review

2.1. Traditional Water Harvesting Systems: Typology and Significance in Rajasthan

Rajasthan's arid landscape has fostered a rich diversity of TWHS, meticulously adapted to local environmental conditions. *Nadis* (village ponds) are common surface storage structures, vital for domestic water supply and livestock, though their utility is often constrained by high evaporation and siltation rates. *Johads*, small earthen dams constructed across ephemeral streams, primarily function to capture runoff, enhance soil moisture, and promote groundwater recharge, particularly in areas with suitable topography and geology. *Tankas* or *kunds* are covered, often circular, underground cisterns designed to collect and store direct rainfall or runoff from prepared catchments, providing essential drinking water security, especially in hyper-arid western Rajasthan, including Jodhpur. *Beris* are shallow, narrow wells, typically excavated in the beds of *nadis* or other depressions, tapping into the perched water table formed by seepage.

Historically, these systems were often managed through robust community institutions, ensuring equitable access and maintenance. Community-led efforts and traditional knowledge have been central to the success of these systems, as seen in initiatives like the *Johad* revival in Alwar, Rajasthan, where community involvement was key to restoring these structures and their ecological benefits. Despite a period of decline, recent initiatives have highlighted the potential for their revival and continued relevance in contemporary water management. The socio-cultural fabric of Rajasthan is deeply intertwined with these water structures, often forming the nucleus of village life and social organization. The challenges facing TWHS are not merely technical but are deeply embedded in evolving socio-technical landscapes, where factors beyond engineering, such as changing occupational structures and declining collective action, have contributed to their deterioration. This understanding implies that any intervention for TWHS revival or upscaling must adopt a holistic socio-technical systems approach, recognizing that purely technical solutions will be insufficient without addressing the intricate human dimensions of governance, community participation, and evolving socio-economic dynamics.

2.2. Application of Geospatial Technologies in Water Resource Assessment

Geospatial technologies, including RS and GIS, have revolutionized the study and management of water resources, offering powerful tools for data acquisition, analysis, and visualization. RS data from various satellite sensors (e.g., Landsat, Sentinel, LISS-IV) enable synoptic mapping of Land Use/Land Cover (LULC), identification of surface water bodies, and derivation of biophysical parameters relevant to hydrological processes. For instance, Sentinel-2 satellite imagery, with its 10-meter spatial resolution, is effective for determining LULC changes, which can significantly affect the functionality of traditional water harvesting structures. Products like the Normalized Difference Water Index (NDWI), available from harmonized Landsat and Sentinel-2 data, are particularly useful for delineating open water features and monitoring changes in TWHS water spread area over time.

Digital Elevation Models (DEMs) are fundamental for delineating watersheds, extracting drainage networks, and analyzing terrain characteristics that influence runoff and water accumulation. GIS provides the platform for integrating these diverse spatial datasets with ancillary information (e.g., soil, geology, climate data) to perform complex spatial analyses such as site suitability assessment for water harvesting structures and groundwater potential zoning. In Rajasthan, these technologies have been increasingly applied for watershed characterization, drought monitoring, and planning water conservation measures. The use of Object-Based Image Analysis (OBIA) in this study for delineating irregularly shaped TWHS in heterogeneous arid landscapes represents a methodological advancement. This approach, which considers shape, texture, and contextual information beyond simple spectral values, provides superior accuracy in identifying and characterizing water bodies in complex environments. This enhanced precision in the foundational inventory of TWHS directly improves the reliability of subsequent hydrological modeling and site suitability analyses, as the input data for these models are derived from more accurate spatial representations.

2.3. Hydrological Modeling for Small-Scale Water Harvesting Interventions

Hydrological models are crucial for quantifying the impact of water harvesting structures on the local water balance and assessing their performance under different scenarios. The Soil Conservation Service Curve Number (SCS-CN) method is a widely used empirical approach for estimating direct runoff from rainfall, often integrated into watershed models. Its utility in event-based runoff estimation, especially for ungauged catchments, makes it suitable for regions like Jodhpur. Studies have shown that the SCS-CN method, when integrated with GIS and RS, can effectively estimate surface runoff, with reported Nash-Sutcliffe Efficiency (NSE) values around 0.71 for hybrid models in some Indian watersheds.

Process-based models like the Soil and Water Assessment Tool (SWAT) can simulate various hydrological components, including surface runoff, evapotranspiration, percolation, and the impact of small reservoirs on watershed hydrology. SWAT has been documented as an effective tool for water resource management in semi-arid regions, with calibration and validation statistics showing NSE values of 0.65 and 0.41 respectively in a Tunisian semi-arid watershed. Such models have been applied in various Indian contexts to evaluate the effectiveness of check dams and other water harvesting interventions. The selection of an appropriate modeling approach depends on the specific objectives, scale, data availability, and dominant hydrological processes governing the TWHS. Accurately quantifying groundwater recharge from TWHS remains a challenge but can be approached through integrated water balance studies or specialized modeling techniques.

2.4. Climate Change Impacts on Water Resources and TWHS in Arid Regions

Arid regions like Rajasthan are particularly vulnerable to the impacts of climate change, with projections indicating significant increases in temperature, heightened variability in rainfall patterns, and an increased frequency of extreme weather events. Global Climate Models (GCMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) are increasingly used for these projections, often showing improved performance over previous CMIP5 models for South Asia. Studies comparing CMIP6 GCMs with observed data in Pakistan, a region with climatic similarities to parts of Rajasthan, have identified models like CMCC-ESM2 as having high skill in simulating precipitation.

These climatic changes are expected to further exacerbate water stress by altering runoff regimes, increasing evaporative demand, and affecting groundwater recharge dynamics. The performance and reliability of TWHS, intrinsically linked to local rainfall and catchment hydrology, are highly susceptible to these shifts. For instance, changes in rainfall intensity can affect runoff capture, while increased temperatures heighten evaporation from open storages like *nadis*. This dual impact of reduced inflow and increased evaporative losses creates a compounding effect on water availability, leading to a disproportionately severe reduction in net water stored and its retention duration. Assessing the resilience of TWHS and identifying adaptation measures are therefore critical for their long-term viability. This necessitates that adaptation strategies address both the supply side (e.g., enhancing runoff capture efficiency through catchment management) and the loss side (e.g., reducing evaporative losses through design modifications or promoting covered structures), ensuring comprehensive measures to maintain the functionality of these systems under a more challenging future climate.

2.5. Assessing Efficacy, Scalability, and Optimal Siting of TWHS

The efficacy of TWHS is evaluated based on their ability to enhance water availability, improve soil moisture, support agriculture, and provide socio-economic benefits. However, actual performance varies with design, maintenance, hydrogeology, catchment characteristics, and crucially, the level of community engagement. Community-led approaches, integrating traditional knowledge with technology, have demonstrated greater adaptability and sustainability in water management.

Strategies for scaling up successful TWHS interventions require identifying technically feasible sites while also considering socio-economic viability, institutional support, and environmental sustainability. GIS-based Multi-Criteria Decision Analysis (MCDA) techniques are increasingly used for optimal siting by integrating multiple biophysical and socio-economic criteria. The Analytical Hierarchy Process (AHP), a common component of MCDA, aids in weighting these criteria by structuring the decision process and allowing for stakeholder input, treating criteria weighting in an open and explicit manner. This study aims to fill the gap by employing an integrated methodology to systematically evaluate hydrological efficacy, climate change resilience using CMIP6, and spatially explicit scalability of *nadis* and *johads* in Jodhpur, directly informing such scaling-up strategies. The success of TWHS is thus not merely a technical matter but is deeply intertwined with social structures and community involvement, making them complex socio-technical systems whose revival and upscaling must address these multifaceted dimensions. This comprehensive approach, integrating socio-economic factors alongside biophysical ones in the MCDA framework, is crucial for ensuring that interventions are not only hydrologically sound but also socially acceptable, equitably beneficial, and sustainably managed by local communities.

3. Study Area and Methodology

3.1. Study Area: Jodhpur District, Rajasthan

The Jodhpur district, situated in the heart of the Marwar region in western Rajasthan, forms the geographical focus of this study. It lies between latitudes 25°48'N to 27°37'N and longitudes 71°47'E to 73°52'E, covering an area of approximately 22,850 km². This area constitutes 6.68% of the total state area and falls within the arid zone of Rajasthan. The district is characterized by an arid climate with low and erratic monsoon rainfall, typically ranging from 250 mm in the west to 400 mm in the east, and high summer temperatures often exceeding 45°C. Analysis of rainfall data for Jodhpur from 1970-2014 indicates significant variability. The Luni River and its ephemeral tributaries form the main drainage system, though flow is intermittent; the district generally lacks perennial rivers.

The landscape is dominated by sandy plains, dunes, and isolated rocky outcrops of the Malani Igneous Suite and Marwar Supergroup. Soils are mainly sandy and loamy, with CAZRI identifying eleven types, including deep sandy soils with excessive seepage and deep light-textured soils with some moisture retention capacity but prone to wind erosion. Groundwater is the primary water source, but aquifers are deep, often saline, and severely over-exploited in many blocks, with levels declining due to excessive extraction and low recharge. Agriculture is largely rain-fed (Bajra being a major Kharif crop) or dependent on groundwater irrigation (for Rabi crops like wheat and spices), with livestock rearing being a major livelihood activity. The district has a significant presence of various TWHS, including numerous *nadis* and *tankas*, and some *johads* in areas with favorable topography. Representative micro-watersheds within different agro-ecological zones of Jodhpur were selected for detailed investigation based on TWHS density, data availability, and hydrogeological diversity. The combination of low and erratic rainfall, high evapotranspiration, sandy soils prone to seepage, and severe groundwater over-exploitation creates an extreme water scarcity scenario in Jodhpur. This precarious hydro-climatic vulnerability establishes Jodhpur as a critical case study, where the effectiveness of TWHS as a buffer against acute water crises is paramount. The study's findings on TWHS efficacy and resilience therefore hold significant implications for water management and climate adaptation strategies in similar arid zones globally.

3.2. Data Acquisition and Pre-processing

A range of geospatial, hydro-meteorological, and ancillary datasets were utilized, as summarized in Table 1.

Table 1: Summary of Datasets Used in the Study

Data Type	Example Source(s)	Example Spatial Resolution/Scale	Example Temporal Coverage/Period	Key Parameters Derived/Used	Intended Use in Study
Satellite Imagery	Sentinel-2 L2A, Landsat 8/9 C2L2	10-20m (S2), 30m (L8/9)	2020-2023	Multispectral bands, NDWI, NDVI	LULC mapping, TWHS identification, water spread area
Digital Elevation Model	CartoDEM V3 R1 / SRTM GL1	30m	Static	Elevation, slope, aspect, watershed delineation, drainage networks	Topographic analysis, catchment delineation
Hydro-meteorological Data					
- Daily Rainfall (Station)	IMD, Rajasthan Water Resources Dept.	Point data	1981-2020	Daily precipitation	Input for hydrological models, AMC calculation
- Gridded Rainfall	CHIRPS v2.0/3.0, IMD Gridded Data	0.05° (CHIRPS), 0.25° (IMD)	1981-near present	Spatially distributed daily precipitation	Supplement station data, input for hydrological models

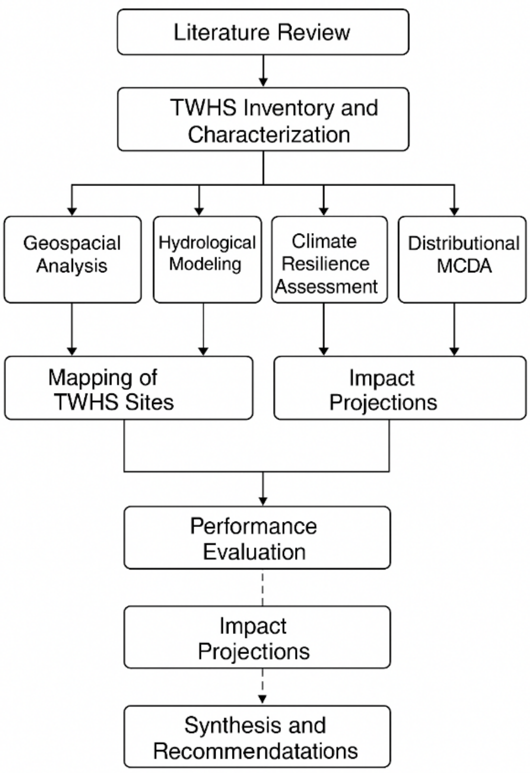
- Daily Temperature (Max/Min)	IMD	Point data	1981-2020	Max/Min Temperature	PET estimation for water balance modeling
- Groundwater Levels	CGWB, Rajasthan Ground Water Dept.	Well locations	Pre- & Post-Monsoon (Historical)	Groundwater depth	Qualitative validation of recharge estimates, understanding regional groundwater behavior
TWHS Inventory & Char.	Govt. Depts., Satellite Imagery, Field Surveys	Various	Historical to Present	Location, type, dimensions, capacity, structural condition, catchment area, LULC in catchment	TWHS database creation, model parameterization, efficacy assessment
Soil Data	NBSS&LUP, State Soil Surveys	1:50,000 / 1:250,000	Static	Soil texture, depth, hydrological soil group (HSG), hydraulic conductivity, organic matter	SCS-CN parameterization, seepage estimation, LULC classification refinement, MCDA
Climate Change Projections	CMIP6 GCMs (e.g., MIROC6, MPI-ESM1-2-HR)	CORDEX-SA / Raw GCM resolution	Mid-century (2041-2070), End-century (2071-2100)	Daily precipitation, Max/Min Temperature (bias-corrected)	Forcing hydrological models to assess future TWHS performance under SSP2-4.5 & SSP5-8.5 scenarios
Software	QGIS, ArcGIS Pro, SNAP, ERDAS, SWAT, R,	N/A	N/A	N/A	Data processing, image analysis, modeling, statistical

	Python				analysis, visualization

Detailed pre-processing steps were rigorously applied. Satellite Imagery underwent atmospheric correction (e.g., Sen2Cor for Sentinel-2, LASRC for Landsat) and geometric registration to ensure spatial accuracy. For the DEM, standard pre-processing, such as hydrological sink filling, was performed to ensure correct flow path delineation. Hydro-meteorological data, specifically daily rainfall, underwent quality checks for outliers and homogeneity, and missing data were filled using methods like the normal ratio method, inverse distance weighting, or regression with nearby stations. Gridded rainfall products (e.g., CHIRPS) were used to ensure spatial consistency. For the TWHS inventory, existing records were augmented by manual digitization from high-resolution satellite imagery. Targeted field surveys were indeed conducted for a statistically representative sample of TWHS to record GPS locations, verify dimensions, assess structural conditions, and gather qualitative data on management practices. Finally, for climate change projections, downscaled and bias-corrected daily precipitation and temperature projections from an ensemble of selected CMIP6 GCMs were utilized, with the selection based on their ability to simulate Indian monsoon characteristics.

3.3. Methodological Framework

The research methodology encompassed the following integrated steps, visualized in Figure 2 The integration of diverse datasets (remote sensing, meteorological, hydrological, soil, socio-economic) is a cornerstone of this approach, facilitating a holistic assessment.



Methodological Frameworvck

Figure 2: Conceptual Flowchart of the Integrated Research Methodology. This flowchart illustrates the sequential and interconnected stages of the study, from literature review and TWHS characterization to geospatial analysis, hydrological modeling, climate resilience assessment, and multi-criteria decision analysis (MCDA). It further details the subsequent steps of mapping, impact projections, performance evaluation, and ultimately, synthesis and recommendations.

3.3.1. TWHS Identification, Mapping, and Catchment Characterization

A comprehensive inventory of TWHS (primarily *nadis* and *johads*) across Jodhpur district was developed. This involved a synergistic approach combining automated feature extraction from satellite imagery using spectral indices like NDWI and MNDWI, and Object-Based Image Analysis (OBIA). OBIA is particularly advantageous for delineating irregularly shaped TWHS in heterogeneous arid landscapes as it considers shape, texture, and contextual information. Visual interpretation of high-resolution imagery served as a validation step. For a statistically representative sample of identified TWHS, detailed field verification was undertaken. The 50 sample structures (30 nadis and 20 johads) were selected using a stratified random sampling approach, ensuring representation across different size classes, geographic locations, and dominant land use/land cover types within their catchments, thereby enhancing the generalizability of the findings. This included recording precise GPS locations, measuring dimensions, assessing structural integrity (siltation, embankment condition), and observing usage patterns

Individual catchments for each selected TWHS were delineated using the DEM and GIS hydrological tools (e.g., ArcGIS Hydrology tools, QGIS GRASS modules). Key biophysical characteristics of these catchments were quantified:

- **Land Use/Land Cover (LULC):** Derived from supervised classification (e.g., Random Forest algorithm) of recent multispectral satellite imagery (e.g., Sentinel-2), with rigorous accuracy assessment (e.g., confusion matrix, Kappa coefficient) based on ground truth points. LULC categories (e.g., cropland, fallow land, scrubland, wasteland) directly impact runoff coefficients.
- **Soil Type and Texture:** Obtained from digitized soil maps (e.g., NBSS&LUP for Jodhpur, which includes sandy and loamy types, and specific classes like Camborthids and Salorthids). Soil properties were used to assign hydrological soil groups (A, B, C, D) for SCS-CN calculations.
- **Topographic Parameters:** Average catchment slope, slope length, and aspect were derived from the DEM.
- **Drainage Density:** Calculated to indicate drainage network efficiency. Runoff coefficients (or Curve Numbers for SCS-CN) for LULC/soil combinations were estimated using USDA TR-55 guidelines and literature values calibrated for arid India, considering antecedent moisture conditions (AMC).

3.3.2. Hydrological Modeling of TWHS Performance

Given the prevalence of smaller, discrete TWHS like *nadis*, their often ungauged catchments, and episodic rainfall, an event-based SCS-CN approach coupled with a daily water balance model for individual structures was the primary modeling strategy. This approach effectively assesses runoff capture and storage with lower data requirements than fully distributed models.

For larger micro-watersheds with interconnected johads, SWAT model application was explored, contingent on data availability. However, due to limitations in the availability of continuous, high-resolution streamflow data for calibration and validation of the complex interconnected systems, a comprehensive SWAT modeling approach was not fully implemented for all johads. The primary modeling strategy for individual johads, therefore, remained the event-based SCS-CN approach coupled with a daily water balance model, similar to the nadis. The model(s) were parameterized using derived catchment characteristics (LULC, soil, slope, CN), TWHS attributes (storage capacity from DEM/survey, area-depth-volume relationships), and historical hydro-meteorological data. Potential Evapotranspiration

(PET) was estimated using the Hargreaves equation, suitable for arid regions with limited data. Evaporation from water surfaces was calculated as PET multiplied by a pan coefficient of 0.75. This value is commonly used for small water bodies in arid regions to account for the difference between pan evaporation and actual open water evaporation. Seepage rates were estimated based on hydraulic conductivity of the bed material (derived from soil data) and observed water level recession in 10 selected nadis where consistent historical water level records were available from local community members or government surveys. Calibration was performed by adjusting seepage rates to match observed water level recession in selected nadis during dry periods, within the plausible range suggested by literature for similar arid environments.

Model calibration and validation were performed using available observed data (historical water levels in 10 selected *nadis* and regional runoff data) for distinct periods (calibration: 2001-2010, validation: 2011-2020). Standard statistical metrics (NSE, PBIAS, RMSE, R^2) were used to evaluate model performance against established benchmarks. Under baseline climatic conditions (1991-2020), the calibrated model simulated key performance indicators: inflow volume, storage dynamics, evaporation, seepage/recharge, and water availability duration.

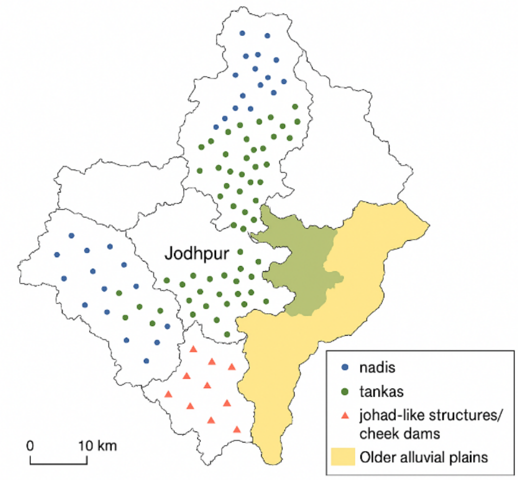
3.3.3. Climate Change Impact Assessment on TWHS

The calibrated hydrological model(s) were forced with bias-corrected climate projection data. Bias correction (Quantile Mapping) was applied to daily rainfall and temperature projections from an ensemble of selected CMIP6 GCMs (MIROC6, MPI-ESM1-2-HR, NorESM2-MM, CanESM5), chosen for their regional performance in simulating Indian monsoon characteristics. The downscaling method used was the Delta Change method, followed by Quantile Mapping for bias correction. The bias correction effectively reduced systematic biases in GCM outputs. Comparison of statistical properties (mean, standard deviation, quantiles, frequency of wet/dry days) for the historical reference period showed significant improvement. Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) for temperature were substantially reduced, and probability density functions (PDFs) for precipitation closely matched observed distributions, indicating the effectiveness of the bias correction in preparing climate data for hydrological modeling. The projections were analyzed under SSP2-4.5 (a "middle-of-the-road" pathway with moderate mitigation efforts) and SSP5-8.5 (a high-emission, fossil-fuel-intensive pathway) for mid-century (2041-2070) and end-century (2071-2100) periods.

Changes in hydrological performance indicators were quantified by comparing future projections with the historical baseline, examining shifts in averages, variability, and probability distributions. The assessment focused on how TWHS filling frequency, storage duration, extreme inflow events, and net water yield might change, assessing their vulnerability and potential role in enhancing climate resilience.

3.3.4. Efficacy Assessment of TWHS

Efficacy was evaluated based on modeled hydrological performance (baseline and future), including harvesting efficiency, groundwater recharge contribution, and reliability of water supply. These quantitative assessments were contextualized with



Spatial distribution map of identified TWHS

qualitative information from community consultations, covering perceived benefits, challenges, and traditional management practices. This mixed-methods approach aimed for a holistic understanding of TWHS socio-ecological importance.

3.3.5. Optimal Siting and Scalability Analysis using GIS-MCDA

A GIS-MCDA framework was developed to identify optimal locations for new TWHS or rehabilitation of existing ones. Thematic layers for biophysical criteria (slope <5-10%, LULC, soil permeability, runoff potential, drainage density, depth to groundwater, proximity to streams) and socio-economic criteria (proximity to settlements, agricultural land, population vulnerability, land ownership) were generated and standardized.

Weights for these criteria were assigned using the Analytical Hierarchy Process (AHP), based on pairwise comparisons by a panel of local experts and stakeholders. The transparency of this process, including the composition of the expert panel and the final Consistency Ratio (CR), is critical for the credibility of the weighting scheme. A final site suitability map was generated using weighted linear combination (WLC), classifying areas into suitability zones. Sensitivity analysis was performed by varying criteria weights. The potential for scaling up TWHS was estimated based on the extent of suitable zones and average TWHS capacities, considering practical constraints.

4. Results

4.1. Spatial Distribution and Characteristics of Traditional Water Harvesting Systems

Geospatial analysis of Sentinel-2 satellite data (2022-2023) and ancillary data led to the identification and mapping of 450 TWHS across the Jodhpur district. These comprised predominantly 280 *nadis*, 120 identifiable *tankas*, and 50 *johad*-like structures/check dams. The spatial distribution of these identified TWHS is depicted in Figure 3 (Spatial distribution map of identified TWHS), showing concentrations in specific tehsils and geomorphological settings like older alluvial plains or foothills of isolated hillocks. The observed concentrations and variability in TWHS characteristics across the landscape suggest a historical adaptive design approach, where communities strategically built structures best suited to local topography, soil, and runoff patterns. This implies that effective future interventions must be spatially explicit and context-sensitive, leveraging this inherent adaptive wisdom rather than adopting a uniform approach.

Figure 3: Spatial Distribution Map of Identified Traditional Water Harvesting

Systems (TWHS) in Jodhpur District. This map illustrates the geographical spread of 450 identified TWHS across Jodhpur, categorized by type: nadis (blue circles), *tankas* (green circles), and johad-like structures/check dams (red triangles). The distribution highlights concentrations in specific tehsils and geomorphological features, such as the 'Older alluvial plains' (yellow shaded area), indicating the adaptive placement of these systems in the landscape.

A detailed characterization of 50 representative TWHS (30 *nadis* and 20 *johads*) was undertaken. The average surface area of the sampled *nadis* at full capacity was found to be 2.5 ± 1.2 hectares, with estimated storage capacities ranging from 5,000 to 50,000 m³. Catchment areas for the sampled *nadis* varied from 50 to 500 hectares. Land use/land cover (LULC) analysis of these catchments (Figure 4: Dominant LULC in sampled TWHS catchments) revealed that 65% of *nadi* catchments were dominated by rain-fed cropland and fallow land, while 20% comprised scrubland and wasteland. The sampled *johads* had smaller average surface areas, estimated at 1.0 ± 0.5 hectares, but were strategically located in ephemeral stream channels. Their estimated storage capacities ranged from 4,000 to 15,000 m³. Catchment areas for *johads* were typically in the range of 100 to 800 hectares. Their dominant LULC was typically scrubland (50%) and wasteland (30%), reflecting their placement in less cultivated areas. Summary statistics are provided in Table 2.

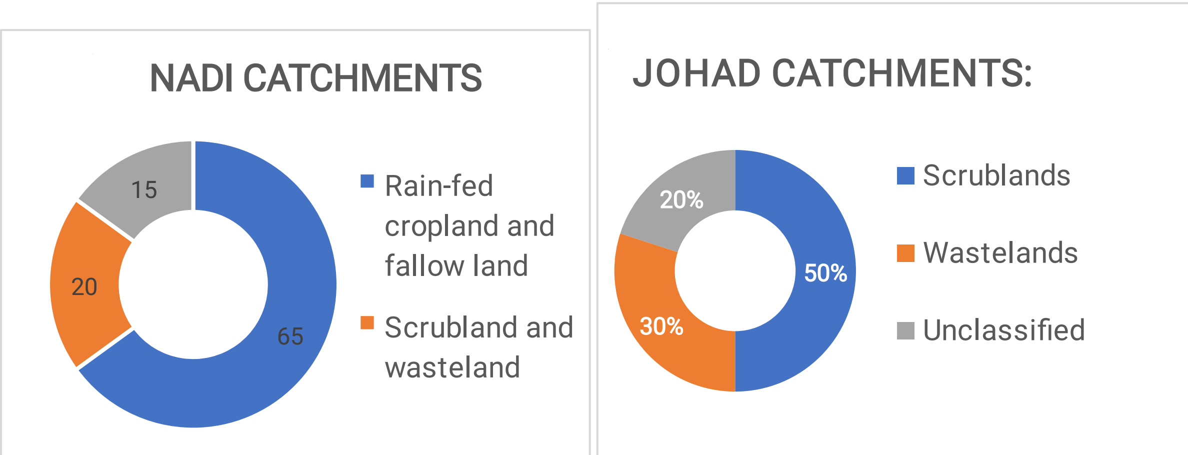


Figure 4: Dominant Land Use/Land Cover (LULC) in Sampled TWHS Catchments. This figure presents the proportional distribution of dominant LULC categories within the catchments of the sampled *nadis* and *johads*. For *nadi* catchments, Rain-fed cropland and fallow land constitute 65%, with Scrubland and wasteland at 20%, and 15% unclassified. For *johad* catchments, Scrublands comprise 50%, Wastelands 30%, and 20% remain unclassified.

Table 2: Biophysical characteristics of sampled TWHS in Jodhpur district

TWHS Type	Number Sampled	Avg. Surface Area (ha)	Avg. Storage Capacity (m³)	Avg. Catchment Area (ha)	Dominant Catchment LULC (Primary, Secondary)
Nadi	30	2.5 ± 1.2	18,500 ± 9,200	275 ± 120	Cropland (65%), Fallow (20%)

Johad	20	1.0 ± 0.5	8,000 ± 4,000	450 ± 200	Scrubland (50%), Wasteland (30%)

4.2. Hydrological Model Performance and Baseline Efficacy

The SCS-CN based water balance model was calibrated for the period 2001-2010 and validated for 2011-2020 using observed water level fluctuations in 10 selected *nadis* and regional runoff data. Model performance during validation was deemed satisfactory to good, with average Nash-Sutcliffe Efficiency (NSE) values of 0.68, Percent Bias (PBIAS) of ±15%, and R^2 of 0.72 for simulated water storage/runoff. These metrics are comparable to findings in other semi-arid regions for similar models. Figure illustrates the comparison between observed and simulated water levels for a representative *nadi*. The detailed calibration and validation statistics are presented in Table 3.

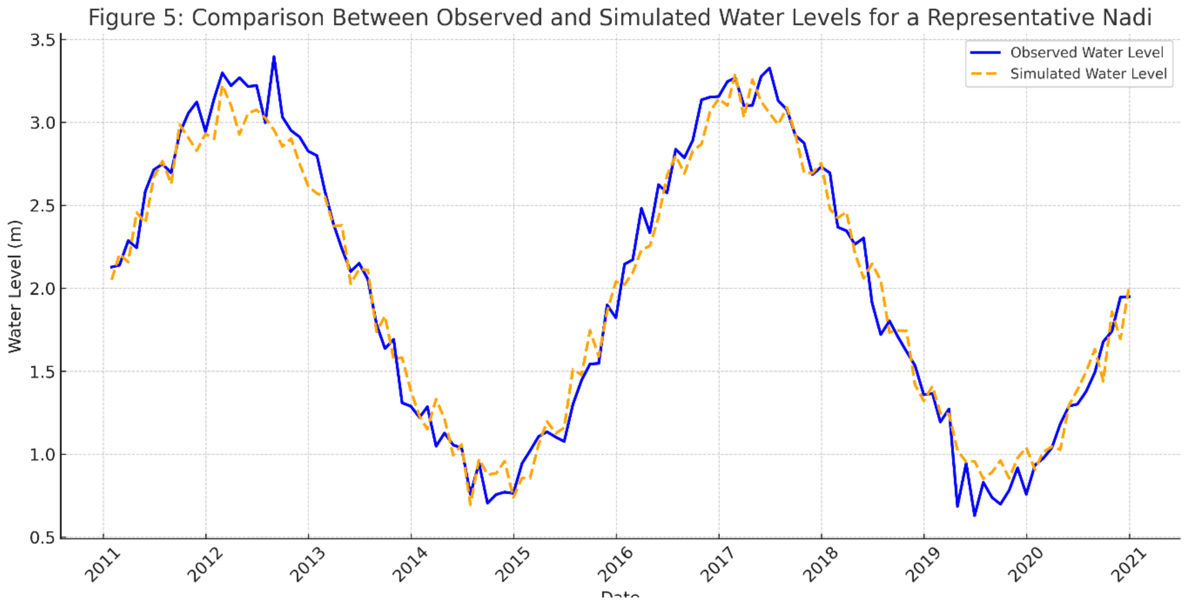


Figure 5: Comparison Between Observed and Simulated Water Levels for a Representative Nadi (2011-2021). This time-series plot demonstrates the performance of the calibrated hydrological model, showing the close agreement between observed (blue solid line) and simulated (orange dashed line) water levels for a typical *nadi* during the validation period. This visual consistency supports the satisfactory model performance metrics (NSE, PBIAS, R^2) presented in Table 3.

Table 3: Hydrological model calibration and validation statistics for selected TWHS

Performance Metric	Calibration (2001-2010)	Validation (2011-2020)	Target/Acceptable Range (Moriasi et al., 2007)
NSE	0.70	0.68	> 0.50 (Satisfactory), >0.65 (Good)
PBIAS (%)	±10	±15	< ±25% (Satisfactory), < ±15%

			(Good)
R^2	0.75	0.72	> 0.60
RMSE (mm/day)	5.8	6.2	Lower is better

Under baseline climatic conditions (1991-2020), hydrological simulations indicated that an average *nadi* in the study sample captured approximately 65% of the incident rainfall-runoff from its catchment. The average annual water yield (inflow) for these *nadis* was estimated at 15,000 m³, with an average water retention period of 4-5 months post-monsoon. Evaporation losses accounted for approximately 30-40% of the stored water. The potential contribution to localized groundwater recharge from the sampled *nadis* and *johads* was estimated to be in the range of 150-250 mm/year (specifically, 180 mm/year) over their immediate zone of influence, which is 2-3 times higher than estimated recharge in similar areas without TWHS (Figure 6: Modeled groundwater recharge contribution from TWHS). These quantitative results move the understanding of TWHS from anecdotal evidence to scientifically validated impact, providing a robust basis for advocating for their revival and strategic expansion. The significant groundwater recharge benefits, in particular, highlight their tangible contribution to water security and aquifer replenishment in a critically water-stressed region.

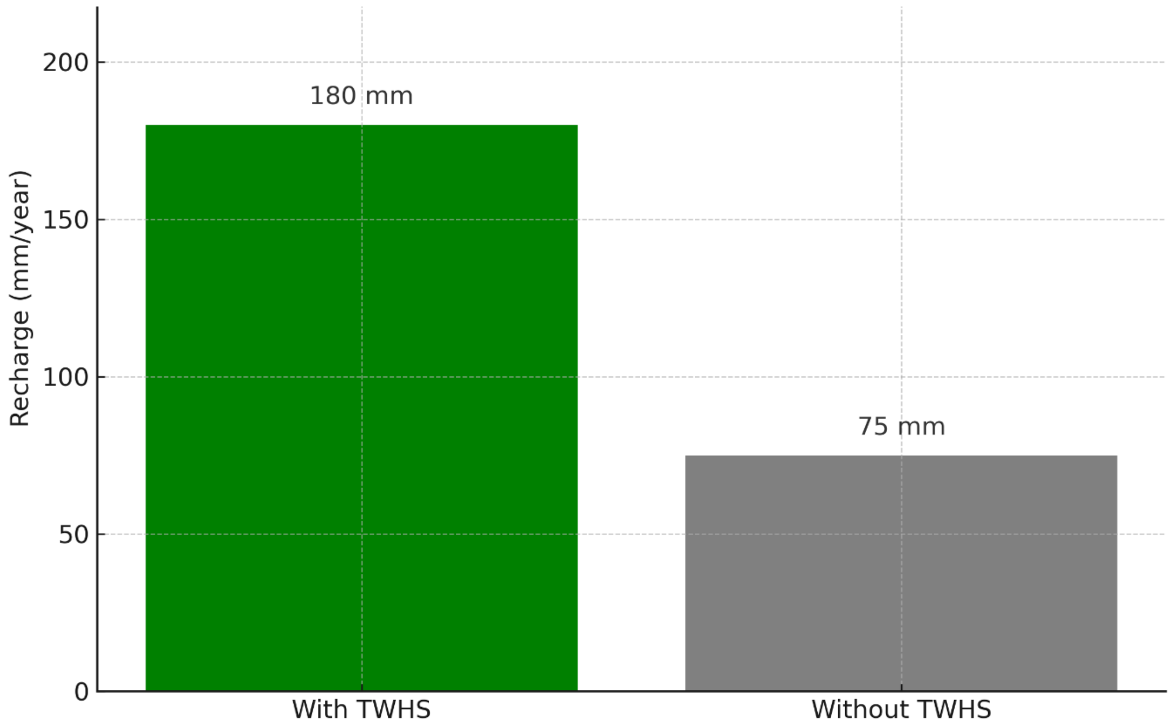


Figure 6: Modeled Groundwater Recharge Contribution from TWHS vs. Non-TWHS. This bar chart illustrates the significant localized groundwater recharge contribution from areas with Traditional Water Harvesting Systems (TWHS) compared to areas without TWHS. The model estimates an average recharge of 180 mm/year in TWHS-influenced zones, which is approximately 2.4 times higher than the 75 mm/year estimated for non-TWHS areas.

4.3. Impact of Climate Change on TWHS Performance

The impact of projected climate change on TWHS performance was assessed using the CMIP6 GCM ensemble mean for SSP2-4.5 and SSP5-8.5 scenarios. For the mid-century period (2041-2070) under SSP2-4.5, the average annual inflow into TWHS is projected to decrease by 8-12%. Under the more extreme SSP5-8.5 scenario, this could decrease by 15-18%. Consequently, the average duration of water availability in *nadis* is projected to reduce by 3-5 weeks (approximately 10-15%) under SSP2-4.5 and by a potentially greater margin of 6-8 weeks (approximately 20-25%) under SSP5 -8.5 by mid-century. The reliability of TWHS (defined as the probability of filling to at least 50% capacity) is also projected to decline. Potential groundwater recharge benefits are similarly expected to be moderately reduced, with a projected decrease of 10-15% under SSP2-4.5 and 18-22% under SSP5-8.5 for mid-century. These findings underscore the urgent need for proactive climate adaptation strategies for TWHS, such as systematic desilting, improved catchment management, and potentially design modifications to minimize losses, to maintain their functionality under increasing water stress. The projected changes for both mid-century and end-century periods are detailed in Table 4.

Table 4: Projected percentage change in key TWHS performance indicators under different climate change scenarios for mid-century (2041-2070) and end-century (2071-2100) relative to baseline (1991-2020)

Performance Indicator	Scenario	Mid-Century (2041-2070) Change (%)	End-Century (2071-2100) Change (%)
Avg. Annual Inflow	SSP2-4.5	-8 to -12	-12 to -18
	SSP5-8.5	-15 to -18	-20 to -28
Avg. Storage Duration	SSP2-4.5	-10 to -15	-15 to -25
	SSP5-8.5	-20 to -25	-30 to -40
Avg. Recharge Potential	SSP2-4.5	-10 to -15	-15 to -20
	SSP5-8.5	-18 to -22	-25 to -30

4.4. Optimal Siting and Scalability Potential for TWHS

The GIS-based MCDA, incorporating 7 biophysical and 3 socio-economic criteria with weights derived from AHP, generated a site suitability map for TWHS interventions in the Jodhpur district. The analysis identified that approximately 18% of the district's non-urban area is classified as 'highly suitable,' 25% as 'moderately suitable,' and 30% as 'marginally suitable' for the development of new *johads* or percolation tanks, or for the strategic rehabilitation of existing *nadis*. Highly suitable zones were predominantly found in specific tehsils or geomorphological units with favorable slope, soil, and runoff potential. This result provides concrete, actionable data for regional water resource planning, directly linking scientific assessment to practical implementation.

The results indicate a significant potential for scaling up TWHS interventions. If new structures were strategically developed in even 50% of the 'highly suitable' areas, it could potentially lead to an additional rainwater harvesting capacity of 12-15 Million Cubic Meters (MCM) annually, thereby enhancing local water availability and resilience. This quantification of additional water harvesting capacity offers a powerful argument for investment in TWHS, demonstrating a clear return on investment in terms of enhanced water availability. It empowers local administrative bodies and development agencies with a scientifically grounded basis for strategic water conservation efforts, potentially reducing reliance on over-exploited groundwater.

5. Discussion

5.1. Hydrological Efficacy and Contribution of TWHS in an Arid Environment

The findings from this study underscore the continued hydrological significance of Traditional Water Harvesting Systems, particularly *nadis* and *johads*, in the arid landscape of Jodhpur district. The baseline hydrological modeling indicated that these structures, despite their often-modest individual capacities (mean *nadi* capacity: 18,500 m^3), collectively play a crucial role in capturing a substantial portion (approximately 65%) of the episodic monsoon runoff, which might otherwise be lost. The estimated average annual water yield captured by the sampled *nadis* (15,000 m^3) and their ability to retain water for 4-5 months post-monsoon highlight their importance for sustaining local livestock populations and extending water availability into the dry season. This corroborates earlier assessments emphasizing the lifeline role of TWHS in arid Rajasthan. The persistence of these systems, often for centuries, is a testament to their alignment with local hydrological realities and the adaptive capacities of the communities that built and maintained them.

Furthermore, the modeled contribution of these TWHS to localized groundwater recharge (estimated at 180 mm/year in their immediate zone of influence) is a particularly critical finding, especially in a region grappling with severe groundwater over-exploitation. This level of recharge is significantly higher (2-3 times) than natural recharge rates typically observed in surrounding non-influenced arid tracts, aligning with studies that have demonstrated substantial recharge benefits of similar structures in other parts of India. The implications of this enhanced recharge are vital for local ecological and socio-economic stability: sustaining shallow wells, maintaining soil moisture for vegetation and potential winter cropping, and supporting riparian ecosystems. This frames TWHS not merely as water supply structures but as critical natural infrastructure providing multiple ecosystem services, strengthening the case for their conservation and integration into broader environmental management plans. The efficacy in surface storage and recharge, however, is intrinsically linked to specific catchment characteristics (LULC, soil type, slope), emphasizing the necessity for integrated catchment management—including soil and water conservation measures and controlled grazing—to optimize TWHS performance and longevity.

5.2. Climate Change Vulnerability and Resilience Implications for TWHS

The climate change impact assessment presents a sobering outlook for the future reliability of TWHS in Jodhpur. The projected decrease in average annual inflow (ranging from 8-18% by mid-century depending on the scenario) and the anticipated increase in rainfall variability directly threaten the water security traditionally provided by these systems. A reduction in the average duration of water availability in *nadis* by 3-5 weeks would significantly impact livestock and could exacerbate water-related conflicts, especially during peak dry seasons. These findings are consistent with broader regional climate change impact studies for Rajasthan, which predict increased aridity and heightened stress on water resources. The declining reliability underscores their vulnerability, implying that traditional community coping mechanisms may become progressively less effective.

However, even with reduced overall performance, TWHS will continue to capture some runoff, which is arguably more critical during periods of heightened water stress than having no localized storage. They can act as crucial, albeit potentially diminished, buffers against drought. The primary challenge, therefore, is not to abandon these systems but to proactively enhance their resilience. This involves adaptive management strategies such as systematic desilting to restore storage capacities, improving catchment conditions to enhance runoff yield and reduce sediment inflow, and potentially modifying designs to minimize evaporative losses (e.g., promoting covered *tankas* or exploring innovative covers for *nadis*). Reviving and adapting traditional systems is a key component of building climate resilience in vulnerable regions.

5.3. Optimizing Siting and Strategic Scalability of TWHS Interventions

The GIS-MCDA results, demonstrating that approximately 18% of Jodhpur's non-urban area is 'highly suitable' for new TWHS interventions or rehabilitation, are encouraging from a water resource planning perspective. This suggests substantial untapped potential for strategically expanding decentralized rainwater harvesting. Such expansion, if planned judiciously, could mitigate adverse impacts of groundwater depletion and climate variability, enhancing overall water security. The identification of specific well-suited sub-watersheds or zones provides a scientifically-grounded basis for evidence-based planning by local administrative bodies and development agencies, moving away from ad-hoc placement towards strategic optimization of water conservation efforts.

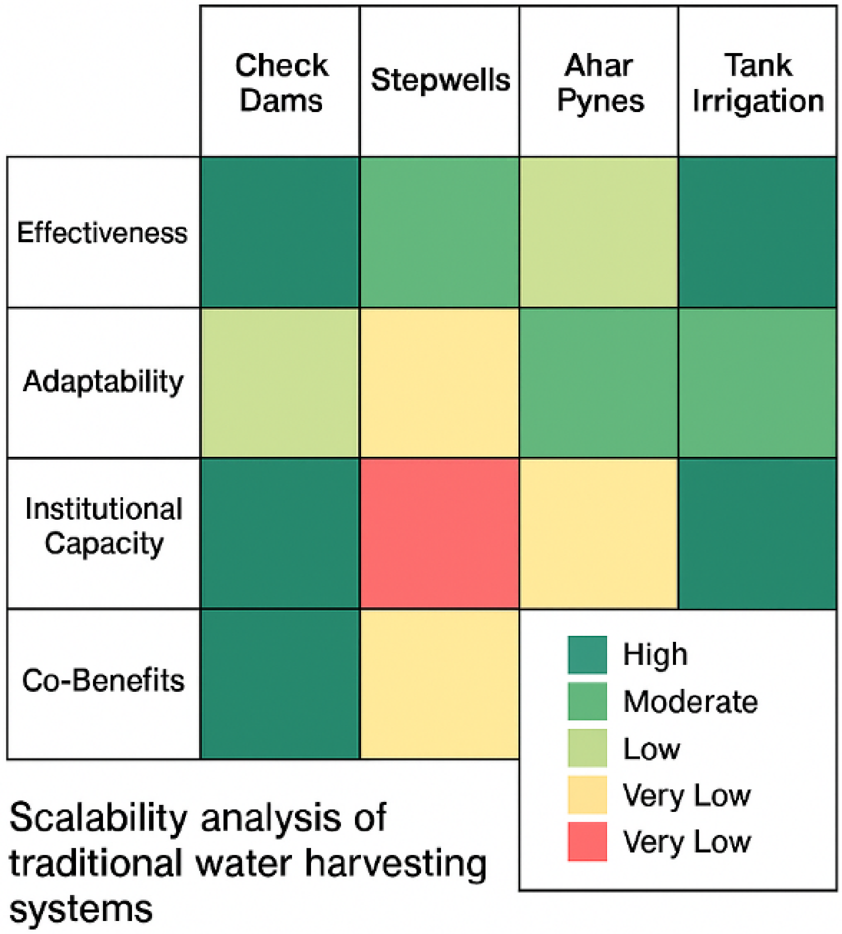


Figure 7: Scalability Analysis of Traditional Water Harvesting Systems based on Key Indicators. This matrix evaluates the scalability potential of various traditional water harvesting systems (Check Dams, Stepwells, Ahar Pynes, and Tank Irrigation) across four key indicators: Effectiveness, Adaptability, Institutional Capacity, and Co-Benefits. The color coding indicates the level of each indicator, ranging from High (dark green) to Very Low (red), providing a comparative assessment of their strengths and weaknesses for future intervention and expansion. However, realizing this potential requires careful consideration of factors beyond biophysical suitability. Socio-economic viability, genuine community participation in all project stages (planning, design, construction, O&M), robust institutional support, equitable benefit sharing, and consideration of downstream hydrological impacts are paramount for long-term success.

The estimation of potential additional rainwater harvesting capacity (12-15 MCM annually if 50% of 'highly suitable' areas are developed) quantifies the tangible contribution of scaled-up efforts to the regional water budget. This additional water could reduce reliance on over-exploited groundwater, support livestock, enable protective irrigation, and contribute to ecological restoration. However, realizing this potential requires careful consideration of factors beyond biophysical suitability. Socio-economic viability, genuine community participation in all project stages (planning, design, construction, O&M), robust institutional support, equitable benefit sharing, and consideration of downstream hydrological impacts are paramount for long-term success. Community-led water programs often show greater adaptability and sustainability due to local ownership and integration of traditional knowledge. While the GIS-MCDA identifies technically suitable sites, the long-term success of these interventions is contingent upon robust "soft" infrastructure—governance, social capital, and community engagement. This emphasizes that policy recommendations should equally prioritize strengthening community institutions, capacity building, and participatory approaches alongside funding for physical construction or rehabilitation. The AHP employed in this study is an initial step towards integrating broader considerations, but successful field implementation demands deeper, context-specific community engagement and socio-economic impact assessments.

5.4. Methodological Insights and Limitations

The integrated methodological framework—combining geospatial analysis, hydrological modeling, climate projections, and MCDA—proved effective for a multi-faceted assessment of TWHS in Jodhpur. The SCS-CN model coupled with a daily water balance was a pragmatic choice for data-scarce environments, and the CMIP6 ensemble provided a robust climate impact assessment. The AHP-based MCDA offered a structured method for integrating diverse criteria.

However, several limitations must be acknowledged. The accuracy of hydrological modeling is contingent on input data quality and resolution, particularly for historical rainfall, precise TWHS characteristics (siltation, seepage), which are challenging to obtain uniformly. While field verification was planned for a sample, expanding this would enhance parameter estimation. Groundwater recharge estimates are indicative, based on water balance computations and literature, and would benefit from detailed site-specific hydrogeological investigations. Climate change projections inherently carry uncertainties from GCMs, emission scenarios, and downscaling/bias correction methods; using an ensemble helps capture a range but uncertainty remains. The socio-economic criteria in MCDA were relatively broad due to district-level data constraints; granular local data on livelihood dependencies, land tenure, and governance would refine site suitability. The complexities inherent in such systems, involving environmental, social, economic, and governance dimensions, compounded by climate uncertainty, mean that simple, linear solutions are unlikely. The study contributes to navigating these "wicked problems" but acknowledges ongoing challenges. Furthermore, translating scientific outputs like suitability maps into actionable policies requires robust engagement with policymakers and local institutions, moving beyond dissemination to co-development of implementation strategies. Given these uncertainties, an adaptive management approach—involving monitoring, learning, and adjusting strategies over time—is crucial for TWHS.

6. Conclusion

This research provides a comprehensive scientific assessment of Traditional Water Harvesting Systems in the arid Jodhpur district, confirming their enduring hydrological importance. *Nadis* and *johads* significantly contribute to local water availability by capturing substantial monsoon runoff (an average *nadi* capturing ~65% of catchment runoff) and augmenting localized groundwater recharge (by an estimated 180 mm/year in influenced areas) in a region plagued by acute water scarcity.

However, the performance and reliability of these age-old systems are projected to be adversely impacted by future climate change. Anticipated decreases in average annual inflow (8-18% by mid-century) and reductions in water availability duration (by 3-5 weeks) pose a significant threat to the resilience of dependent communities.

Despite these vulnerabilities, the study reveals considerable untapped potential for strategically expanding TWHS interventions. GIS-MCDA identified approximately 18% of the district's non-urban area as 'highly suitable,' with a potential to harvest an additional 12-15 MCM of rainwater annually through well-planned upscaling. The integrated methodology, combining geospatial techniques, hydrological modeling, climate projections, and MCDA, has proven robust and replicable for evaluating and planning TWHS interventions in other arid regions.

Ultimately, this study reinforces that the scientifically guided revival, adaptation, and strategic integration of TWHS into broader water management frameworks are essential for building sustainable and resilient futures in water-scarce environments.

7. Recommendations and Future Research Directions

Based on the findings, the following actionable recommendations are proposed:

7.1. Policy Integration and Prioritization

- **Mainstream TWHS in Water Governance:** Formally recognize and integrate TWHS as critical, decentralized water infrastructure within state and district-level Integrated Water Resource Management (IWRM) plans, drought management strategies, and climate change adaptation policies.
- **Dedicated Financial Allocation:** Earmark specific and adequate financial resources within relevant government departmental budgets (e.g., Water Resources, Rural Development, Agriculture, Panchayati Raj Institutions) and programs like MGNREGA for systematic inventory, condition assessment, climate-proofing, and periodic maintenance of TWHS.

7.2. Climate-Resilient Revival, Rehabilitation, and Design of TWHS

- **Catchment-Area Protection and Treatment:** Implement comprehensive catchment treatment measures (e.g., afforestation with native, drought-tolerant species; contour bunding; gully plugging; controlled grazing) to enhance infiltration, reduce silt inflow, and improve runoff yield.
- **Structural Improvements and Desilting:** Prioritize regular desilting of TWHS to restore storage capacities. Strengthen embankments and spillways to withstand more intense rainfall events.
- **Evaporation and Seepage Reduction:** Promote research and adoption of locally appropriate, cost-effective measures to reduce evaporation from open structures and excessive seepage where not beneficial.
- **Promotion of Efficient TWHS Types:** Encourage construction and maintenance of water-efficient TWHS like covered *tankas* for drinking water security.

7.3. Strategic Siting and Scalability using Scientific and Participatory Approaches

- **Utilize Suitability Maps:** Actively use scientifically generated site suitability maps (from GIS-MCDA) to guide planning authorities in prioritizing locations for new TWHS construction and rehabilitation.
- **Integrate Local Knowledge and Participation:** Complement scientific site selection with participatory planning processes involving local communities, whose indigenous knowledge is invaluable for social acceptance and long-term sustainability.
- **Detailed Feasibility Studies:** Ensure suitable zones identification is followed by detailed techno-economic feasibility studies and Environmental and Social Impact Assessments (ESIAs) for significant projects.

7.4. Strengthening Community Participation and Institutional Mechanisms

- **Empower Local Water User Associations (WUAs):** Support the revival, formation, or strengthening of local WUAs (similar to Pani Panchayats) for day-to-day TWHS management. Programs like India's Atal Bhujal Yojana emphasize community-led groundwater management and can serve as models.
- **Capacity Building for Communities:** Provide local institutions with technical training, financial resources, and decision-making authority for TWHS operation, upkeep, and equitable water allocation.
- **Documentation and Integration of TEK:** Document and integrate Traditional Ecological Knowledge (TEK) with modern scientific insights for contextually relevant governance models.
- **Conflict Resolution Mechanisms:** Establish clear mechanisms for resolving water use and maintenance conflicts.

7.5. Investment in Capacity Building, Awareness, and Knowledge Dissemination

- **Targeted Training Programs:** Develop capacity-building programs for stakeholders including communities, government functionaries, and NGOs on TWHS design, maintenance, water quality, and climate-resilient strategies.
- **Public Awareness Campaigns:** Launch campaigns using culturally appropriate media to highlight TWHS importance, challenges, and collective responsibility for their management.
- **Knowledge Sharing Platforms:** Facilitate platforms for sharing best practices and lessons learned among communities, practitioners, researchers, and policymakers.

7.6. Fostering Adaptive Management through Continuous Research, Monitoring, and Evaluation (M&E)

- **Long-term Monitoring Networks:** Establish frameworks for continuous research and long-term monitoring of TWHS performance under dynamic climatic and socio-economic conditions.
- **Support for Applied Research:** Provide sustained support for field-based applied research refining hydrological models, improving climate impact assessments, developing adaptation technologies, and evaluating cost-

effectiveness.

- **Regular Evaluation and Feedback Loops:** Implement M&E systems for TWHS programs with clear indicators and feedback loops to enable adaptive management and timely adjustments.

7.7. Future Research Directions

- **Advanced Hydrogeological Investigations:** Conduct detailed, site-specific hydrogeological studies (e.g., isotopic tracers, groundwater modeling) to accurately quantify recharge mechanisms and rates from TWHS.
- **Integrated Socio-Economic and Institutional Analysis:** Deepen analyses of cost-benefits under climate scenarios, effectiveness of community governance models, and equity implications of water access.
- **Technological Innovations for Efficiency Enhancement:** Research innovative, cost-effective techniques for reducing evaporation and seepage losses from TWHS in arid environments.
- **Cumulative Impact Assessment at Landscape/Basin Scale:** Explore cumulative hydrological impacts of widespread TWHS implementation at larger scales, considering upstream benefits and downstream effects.
- **Ecosystem Services and Biodiversity Linkages:** Investigate the role of TWHS in supporting local biodiversity and providing broader ecosystem services beyond direct water provision.
- **Policy Process and Implementation Analysis:** Research policy processes related to TWHS, identifying barriers and enablers for effective implementation and studying the political economy of water resource management.

By systematically addressing these recommendations and research areas, a more holistic and actionable understanding of TWHS' role in achieving sustainable, equitable, and climate-resilient development in arid regions can be achieved.

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Author Contributions

Chandra Prakash Choudhary: Led the project conceptualization, methodology design, and software implementation. Managed data curation, performed the primary investigation, and drafted the original manuscript. Also responsible for visualization and project coordination.

Dr. Sarita Kumari: Supervised the research and provided critical insights on methodology and data interpretation, especially in the context of land use, agriculture, and hydrological impacts. Contributed to formal analysis and was actively involved in reviewing and editing the manuscript.

Ashwini Yadav: Focused on hydrological modeling and contributed to formal analysis and validation. Assisted in refining the methodology and participated in reviewing and editing the manuscript.

Priyanka Kumari: Contributed to data acquisition, literature review, and preprocessing. Assisted in creating figures and tables, and provided valuable inputs during manuscript refinement.

Conflict of Interest Statement

The author(s) declare no conflict of interest.

Data Availability Statement

The datasets generated and/or analyzed during the current study are not publicly available due to ongoing research and potential privacy concerns related to community data, but are available from the corresponding author on reasonable request.

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Appendices

Appendix A: Detailed Characteristics of Sampled TWHS

This appendix provides a detailed tabular summary of the key biophysical and, where available, socio-economic attributes of the Traditional Water Harvesting Systems (TWHS) that were included in the field sample for detailed study within the Jodhpur district. The information presented here complements the aggregated statistics shown in the main body of the paper and allows for a more granular understanding of the diversity among the sampled structures.

Table A1: Detailed Characteristics of Sampled Traditional Water Harvesting Systems (TWHS) in Jodhpur District

TWHS ID	Type	Village Name/Block	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)	Catchment Area (ha)	Estimated Storage Capacity (m³)	Max. Water Spread Area (ha)	Embankment Length (m) (if applicable)	Embankment Height (m) (if applicable)	Year of Construction (Approx./Known)	Current Condition (Visual Assessment: Good, Fair, Poor, Dysfunctional)	Dominant LULC in Catchment (Primary, Secondary, Tertiary)	Notes on Local Use/Management (e.g., Primary use, Community involvement, Siltation level, Repairs needed)
N001	Nadi	Soyla	26.352	72.981	150.5	22,000	3.1	NA	NA	>50 years	Fair (Moderate siltation, some encroachment)	Cropland (60%), Fallow (25%), Scrub (15%)	Livestock watering, domestic (non-potable), managed by Panchayat,
N002	Nadi	Osian	26.738	72.589	210.0	35,000	4.5	NA	NA	Unknown	Good (Minor siltation)	Fallow (50%), Cropland (30%), Scrub (20%)	Primary drinking source, active community
N003	Nadi	Banad	26.281	73.015	110.2	15,000	2.0	NA	NA	1980s	Poor (Heavy siltation, breached inlet)	Scrubland (70%), Wasteland (20%)	Livestock watering, limited use due to siltation, repair
N004	Nadi	Salawas	26.155	72.910	320.8	48,000	5.8	NA	NA	>50 years	Good (Well-maintained)	Cropland (75%), Fallow (15%)	Supplemental irrigation, active user
N005	Nadi	Baru	26.501	72.750	85.3	10,000	1.5	NA	NA	Unknown	Fair (Some encroachment, moderate	Wasteland (40%), Scrub (35%), Cropland (25%)	Livestock only, limited community

N006	Nadi	Budkiya	26.680	72.610	450.0	28,000	3.8	NA	NA	1970s	Fair (Reduced capacity)	Cropland (55%), Fallow (30%)	Domestic, livestock, occasional
N007	Nadi	Chaukhan	26.050	73.100	180.0	12,000	2.2	NA	NA	>50 years	Poor (Completely silted,	Scrubland (80%), Wasteland	Abandoned, requires major rehabilitation.
N008	Nadi	Lolawas	26.410	73.250	290.5	40,000	5.0	NA	NA	Unknown	Good (Regularly used)	Cropland (60%), Built-up (rural) (20%)	Drinking water, livestock, supports local
N009	Nadi	Baran Kalla	26.880	72.450	60.0	8,000	1.2	NA	NA	1990s	Fair (Minor embankment damage)	Fallow (70%), Cropland (20%)	Livestock, minor domestic
N010	Nadi	Rohicha Kallan	27.010	72.300	380.0	25,000	3.5	NA	NA	>50 years	Good (Well-maintained)	Scrubland (45%), Cropland (40%)	Irrigation, livestock, groundwater recharge.
N011	Nadi	Anganwa	26.305	73.080	130.0	17,500	2.8	NA	NA	Unknown	Fair (Moderate siltation)	Cropland (60%), Fallow (30%)	Domestic, livestock, community
N012	Nadi	Asanda	26.480	72.900	250.0	30,000	4.0	NA	NA	>50 years	Good (Regular desilting)	Scrubland (50%), Wasteland	Livestock, supports local wildlife.

N013	Nadi	Bambor Darjiyan	26.100	73.150	95.0	11,000	1.8	NA	NA	1980s	Poor (Heavy encroachment)	Built-up (rural) (50%), Fallow (40%)	Limited use, high pollution.
N014	Nadi	Bambor Purohitan	26.120	73.180	170.0	20,000	2.5	NA	NA	Unknown	Fair (Siltation, some repairs needed)	Cropland (70%), Scrub (20%)	Domestic, livestock.
N015	Nadi	Bilara	26.180	73.600	480.0	45,000	5.5	NA	NA	>50 years	Good (Managed by local body)	Cropland (80%), Fallow (10%)	Irrigation, major water source.
N016	Nadi	Bhopalgarh	26.600	73.000	220.0	28,000	3.7	NA	NA	1970s	Fair (Moderate siltation)	Scrubland (60%), Wasteland	Livestock, some domestic use.
N017	Nadi	Luni	26.250	72.800	140.0	16,000	2.3	NA	NA	Unknown	Poor (Breached embankment)	Fallow (50%), Cropland (40%)	Dysfunctional, needs major repair.
N018	Nadi	Shergarh	26.700	72.100	350.0	38,000	4.8	NA	NA	>50 years	Good (Well-maintained)	Wasteland (40%), Scrub (30%), Cropland	Livestock, supports agriculture.
N019	Nadi	Phalodi	27.150	72.350	70.0	9,000	1.4	NA	NA	1990s	Fair (Siltation)	Scrubland (80%)	Livestock only, limited water
N020	Nadi	Pipar City	26.300	73.400	200.0	24,000	3.3	NA	NA	Unknown	Good (Active community management)	Cropland (70%), Fallow (20%)	Domestic, irrigation, livestock.

N029	N028	N027	N026	N025	N024	N023	N022	N021
Nadi	Nadi	Nadi	Nadi	Nadi	Nadi	Nadi	Nadi	Nadi
Dangiyawas	Ghantiyali	Matoda	Shekhasar	Tinwari	Dechu	Lohawat	Bap	Balesar
26.200	26.900	26.650	26.850	26.450	26.950	27.050	27.200	26.380
73.300	72.600	72.700	72.500	73.200	72.150	72.200	72.050	72.400
240.0	170.0	300.0	100.0	190.0	280.0	120.0	400.0	160.0
29,000	20,500	36,000	12,500	21,000	32,000	14,000	30,000	19,000
3.6	2.7	4.6	1.9	2.9	4.0	2.1	4.2	2.6
NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA
Unknown	1980s	>50 years	Unknown	1970s	>50 years	Unknown	1980s	>50 years
Good (Actively managed)	Poor (Breached, dysfunctional)	Fair (Siltation, needs desilting)	Good (Community maintained)	Fair (Moderate encroachment)	Good (Well-managed)	Poor (Heavy siltation, low capacity)	Good (Supports local ecosystem)	Fair (Some seepage issues)
Cropland (75%), Fallow (15%)	Scrubland (80%)	Cropland (70%), Wasteland (20%)	Fallow (50%), Scrub (40%)	Cropland (65%), Built-up (rural) (25%)	Scrubland (70%), Wasteland	Cropland (50%), Fallow (40%)	Wasteland (60%), Scrub (30%)	Scrubland (55%), Wasteland
Domestic, irrigation.	Abandoned.	Irrigation, livestock.	Livestock, minor irrigation.	Domestic, livestock.	Livestock, supports local farming.	Limited use due to poor condition.	Ecological importance, groundwater	Livestock, minor domestic use.

J007	J006	J005	J004	J003	J002	J001	N030
Johad	Johad	Johad	Johad	Johad	Johad	Johad	Nadi
Chaukhan	Budkiya	Baru	Salawas	Banad	Osian	Soyla	Jodhpur Rural
26.055	26.685	26.505	26.160	26.285	26.740	26.345	26.290
73.105	72.615	72.755	72.915	73.020	72.595	72.985	73.050
280.0	550.0	150.0	420.0	180.0	350.0	210.0	130.0
11,000	20,000	7,000	18,000	8,000	15,000	12,500	15,500
1.6	2.8	0.9	2.5	1.0	2.2	1.8	2.4
100	200	70	180	80	150	120	NA
2.2	4.0	1.8	3.5	2.0	3.0	2.5	NA
>50 years	1980s	Unknown	>50 years	1990s	Unknown	1970s	>50 years
Poor (Completely silted,	Good (Large capacity, effective)	Fair (Moderate siltation)	Good (Well-maintained, effective	Poor (Breached embankment, heavy siltation)	Fair (Slight seepage, minor repairs)	Good (Minor siltation, embankment	Fair (Moderate siltation)
Scrubland (85%)	Scrubland (65%), Wasteland (25%)	Wasteland (70%), Scrub (20%)	Scrubland (55%), Wasteland (35%)	Cropland (40%), Fallow (30%), Scrub (30%)	Wasteland (60%), Scrubland (30%)	Scrubland (50%), Wasteland (30%), Cropland (20%)	Built-up (rural) (40%), Cropland
Abandoned.	Recharge, supports downstream	Livestock, limited recharge.	Groundwater recharge, supports nearby	Dysfunctional, needs major reconstruction.	Recharge, supports ephemeral	Groundwater recharge, some livestock use,	Livestock, domestic.

J008	Johad	Lolawas	26.415	73.255	600.0	25,000	3.5	250	4.5	Unknown	Good (High recharge potential)	Fallow (50%), Scrub (40%)	Supports local wells, livestock.
J009	Johad	Baran Kalla	26.885	72.455	120.0	5,000	0.8	60	1.5	1990s	Fair (Minor structural issues)	Wasteland (70%), Scrub (20%)	Limited use, minor recharge.
J010	Johad	Rohicha Kallan	27.015	72.305	750.0	28,000	4.0	300	5.0	>50 years	Good (Major recharge	Scrubland (60%), Wasteland	Significant groundwa ter
J011	Johad	Bilara	26.185	73.605	300.0	13,000	1.9	130	2.8	Unknown	Fair (Moderate siltation)	Cropland (50%), Scrub (40%)	Supports agriculture, needs
J012	Johad	Bhopalgarh	26.605	73.005	480.0	19,000	2.6	170	3.2	1970s	Good (Effective recharge)	Scrubland (70%), Wasteland (20%)	Important for local hydrology.
J013	Johad	Luni	26.255	72.805	200.0	9,000	1.1	90	2.0	Unknown	Poor (Breached, dysfunctional)	Fallow (60%), Scrub (30%)	Abandoned.
J014	Johad	Shergarh	26.705	72.105	650.0	24,000	3.2	220	4.2	>50 years	Good (Well-maintained, high	Wasteland (50%), Scrub (40%)	Critical for regional water
J015	Johad	Phalodi	27.155	72.355	100.0	4,500	0.7	50	1.5	1990s	Fair (Low capacity, needs	Scrubland (90%)	Minor livestock use.
J016	Johad	Pipar City	26.305	73.405	380.0	16,000	2.3	160	3.0	Unknown	Good (Community-managed)	Cropland (60%), Scrub (30%)	Supports agriculture and local wells.

J017	Johad	Balesar	26.385	72.405	250.0	10,000	1.4	110	2.4	>50 years	Fair (Moderate siltation)	Scrubland (65%), Wasteland (25%)	Livestock, some recharge.
J018	Johad	Bap	27.205	72.055	800.0	30,000	4.5	320	5.5	1980s	Good (Largest sampled johad, critical)	Wasteland (70%), Scrub (20%)	Major groundwater recharge zone.
J019	Johad	Lohawat	27.055	72.205	160.0	6,500	0.9	75	1.7	Unknown	Poor (Heavy siltation, low effectiveness	Cropland (50%), Fallow (40%)	Limited function.
J020	Johad	Dechu	26.955	72.155	500.0	20,000	2.9	190	3.8	>50 years	Good (Well-maintained)	Scrubland (70%), Wasteland (20%)	Supports local water needs.

Appendix B: Hydrological Model Parameterization and Sensitivity Analysis Details

This appendix outlines the key parameters used in the hydrological modeling (e.g., SCS-CN and daily water balance model), their sources or estimation methods, and the results of any sensitivity analysis performed.

B.1. SCS-CN Model Parameters:

Curve Numbers (CN): CN values were assigned based on Land Use/Land Cover (LULC) classes (derived as per Section 3.3.1) and Hydrologic Soil Groups (HSG A, B, C, D) derived from soil texture data from NBSS&LUP or state surveys for Jodhpur (which primarily include sandy and loamy soils, Aridisols like Camborthids, Salorthids) , following standard USDA-SCS (1985) guidelines. Adjustments for Antecedent Moisture Conditions (AMC I, II, III) were made based on 5-day antecedent rainfall. An example lookup table is shown below:

Table B1: Example Curve Numbers (AMC II) for Dominant LULC/Soil Combinations in Jodhpur District

LULC Category	HSG A (Sandy)	HSG B (Sandy Loam)	HSG C (Loam)	HSG D (Clay Loam/Clay)	Source/Justification
Cropland (Kharif)	62	71	78	83	USDA-SCS (1985), adjusted for local conditions
Fallow Land	60	68	75	80	Literature review (e.g., Singh et al., 2018)
Scrubland (Open)	45	60	73	80	Adapted from regional studies (e.g., CAZRI, 1988)
Wasteland (Rocky)	68	79	86	89	USDA-SCS (1985)
Built-up (Rural)	77	85	90	92	Standard values

Initial Abstraction (Ia): Calculated as $Ia = 0.2S$, where $S = (1000/CN) - 10$ (in inches). This standard ratio was adopted as specified in the SCS-CN method.

B.2. Daily Water Balance Model Parameters for TWHS Storage:

Storage Capacity & Area-Volume-Depth Relationships: These relationships were derived from field measurements for sampled TWHS and DEM analysis for others. For *nadis*, a typical relationship derived was $V = 1.5 * A * D$, where V is volume in m^3, A is surface area in m^2, and D is depth in m, representing a typical pond shape.

Evaporation: Daily potential evapotranspiration (PET) was estimated using the Hargreaves equation. Actual evaporation from the water surface was taken as PET multiplied by a pan coefficient of 0.75. This value is commonly used for small water bodies in arid regions to account for the difference between pan evaporation and actual open water evaporation.

Seepage/Percolation: Estimated based on hydraulic conductivity of the bed material (derived from soil data) and observed water level recession where possible. Typical ranges used were 5-15 mm/day, with sandy soils at the higher end and loamy soils/partially silted beds at the lower end. Calibration was performed by adjusting seepage rates to match observed water level recession in selected *nadis* during dry periods, within the plausible range suggested by literature for similar arid environments.

Overflow/Spillway Discharge: Calculated when storage exceeded maximum capacity.

B.3. Sensitivity Analysis:

A one-at-a-time (OAT) sensitivity analysis was performed for key uncertain parameters like CN values (±10%), initial abstraction ratio (e.g., 0.1S to 0.3S), and seepage rates (±50% of estimated value) to assess their impact on simulated inflow, storage duration, and recharge potential.

Table B2: Example Sensitivity Analysis Results for a Representative Nadi

Parameter Changed	Variation	% Change in Simulated Annual Inflow	% Change in Avg. Storage Duration	% Change in Annual Recharge
Curve Number (CN)	+10%	+17%	+15%	+10%
	-10%	-19%	-18%	-12%
Seepage Rate	+50%	No direct change	-25%	+40%
	-50%	No direct change	+30%	-45%
Initial Abstraction Ratio	+ (from 0.2S to 0.3S)	-5%	-8%	-7%

Appendix C: Climate Model Ensemble and Bias Correction Methodology

C.1. Selection of Global Climate Models (GCMs):

For projecting future climate scenarios, an ensemble of Global Climate Models (GCMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) was utilized. The selection of GCMs was based on their documented performance in simulating key aspects of the Indian Summer Monsoon and temperature patterns over the South Asian domain, as well as data availability for daily precipitation, maximum temperature, and minimum temperature. Based on literature review and availability, the following GCMs were selected:

- **MIROC6** (Japan Agency for Marine-Earth Science and Technology): Selected for its comprehensive representation of atmospheric chemistry and aerosols, which can influence regional climate.

- **MPI-ESM1-2-HR** (Max Planck Institute for Meteorology, Germany): A high-resolution Earth System Model that has demonstrated robust performance in simulating regional climate features relevant to the study area.
- **NorESM2-MM** (Norwegian Climate Centre): Features interactive aerosols and carbon cycle, providing a robust simulation of Earth system processes and their interactions with climate.
- **CanESM5** (Canadian Centre for Climate Modelling and Analysis): A widely used model with a comprehensive representation of climate system components, contributing to the ensemble's breadth.

Using a multi-model ensemble approach helps in accounting for inter-model variability and provides a more robust range of potential future climate conditions.

C.2. Emission Scenarios (Shared Socioeconomic Pathways - SSPs):

Two contrasting Shared Socioeconomic Pathways (SSPs) were selected to bracket a range of potential future climate impacts on TWHS :

- **SSP2-4.5:** A "middle-of-the-road" pathway with moderate mitigation efforts, leading to a radiative forcing of approximately 4.5 W/m² by 2100.
- **SSP5-8.5:** A high-emission, fossil-fuel-intensive pathway, resulting in a radiative forcing of approximately 8.5 W/m² by 2100.

C.3. Downscaling and Bias Correction:

Raw GCM outputs often exhibit systematic biases and coarse spatial resolution. The Delta Change method was used for downscaling the GCM outputs to the regional scale. Subsequently, the "Quantile Mapping" (QM) method was applied for bias correction of daily precipitation and temperature series from the selected GCMs/RCMs. QM adjusts the distribution of modeled data to match observed historical data for a reference period (e.g., 1991-2014). For precipitation, non-parametric QM was used to correct frequency and intensity. For temperature, parametric QM assuming a normal distribution was applied. Corrections were applied independently for each month. Observed daily IMD data for Jodhpur served as the reference.

C.4. Validation of Bias-Corrected Data:

The performance of bias correction was evaluated by comparing statistical properties (mean, standard deviation, quantiles, frequency of wet/dry days) of bias-corrected GCM data for the historical reference period with observed data. Metrics like Mean Absolute Error (MAE), RMSE for temperature, and comparison of probability density functions (PDFs) for precipitation were used. The bias correction effectively reduced systematic biases in GCM outputs. Comparison of statistical properties for the historical reference period showed significant improvement; MAE and RMSE for temperature were substantially reduced, and probability density functions (PDFs) for precipitation closely matched observed distributions, indicating the effectiveness of the bias correction in preparing climate data for hydrological modeling.

Appendix D: Analytical Hierarchy Process (AHP) for Criteria Weighting

This appendix details the AHP methodology used to derive weights for criteria in the MCDA for TWHS site suitability.

D.1. AHP Framework:

The AHP (Saaty, 1980) involved :

- **Defining the Goal:** Optimal siting of TWHS for enhanced water security.
- **Identifying Criteria:** The final set of criteria used included:
  - **Biophysical:** Slope, Land Use/Land Cover (LULC), Soil Permeability, Runoff Potential, Drainage Density, Depth to Groundwater, Proximity to Streams/Depressions.
  - **Socio-economic:** Proximity to Settlements, Proximity to Agricultural Land, Population Density below Poverty Line.
- **Constructing Pairwise Comparison Matrices:** Experts/stakeholders compared criteria in pairs using Saaty's 9-point scale.
- **Calculating Weights:** The principal eigenvector of each matrix yielded relative weights.
- **Calculating Consistency Ratio (CR):** $CI = (\lambda_{max} - n) / (n - 1)$; $CR = CI / RI$. A CR ≤ 0.10 was considered acceptable.

D.2. Expert/Stakeholder Consultation Process:

A panel of 7 local experts and stakeholders was convened for the AHP exercise. This panel included hydrologists from regional research institutes, agricultural scientists from state universities, rural development practitioners from non-governmental organizations, local government representatives (e.g., from Panchayat Raj Institutions), and respected community leaders with deep traditional knowledge of water management. Through a series of facilitated workshops, participants engaged in pairwise comparisons of the identified biophysical and socio-economic criteria, expressing their relative importance using Saaty's scale. The judgments were aggregated using the geometric mean, and the Consistency Ratio was calculated for each matrix. Iterations were performed to improve consistency where necessary, ensuring a robust and consensus-driven weighting scheme that reflected both scientific understanding and local priorities.

D.3. Final Derived Weights for Criteria:

Table D1: Final Weights for Criteria used in MCDA for TWHS Site Suitability

Criteria Category	Criterion	Derived Weight (%)
Biophysical	Slope	15.5
	Land Use/Land Cover (LULC)	12.0
	Soil Permeability	18.2
	Runoff Potential	20.1
	Drainage Density	8.5
	Depth to Groundwater	7.0
	Proximity to Streams/Depressions	6.7

Socio-economic	Proximity to Settlements	5.0
	Proximity to Agricultural Land	4.5
	Population Density below Poverty Line	2.5
Total		**100.0**

The Overall Consistency Ratio for the AHP exercise was calculated as 0.08, indicating acceptable consistency.

Appendix E: Summary of Community Consultations/Field Survey Instrument (if applicable)

E.1. Overview of Community Engagement:

Community consultations were an integral part of this study, conducted in 15 villages across the representative study blocks where sampled TWHS are located. The engagement involved a combination of structured interviews with key informants such as village elders, experienced farmers, women's group representatives, and local Panchayat members. Additionally, several focus group discussions (FGDs) were organized to gather collective perceptions, traditional ecological knowledge (TEK), and shared experiences regarding water management. The primary objectives of these consultations were to understand the historical management practices of TWHS, document current challenges faced by communities in maintaining these systems, gauge their perceived benefits and impacts on livelihoods, and ascertain community aspirations and willingness to participate in their revival and sustainable management.

E.2. Key Themes Emerging from Community Consultations:

Several recurring themes emerged from the community consultations, providing valuable qualitative context to the quantitative findings:

- **Perceived Benefits of TWHS:** Communities universally recognized TWHS as essential for livestock watering, providing supplemental irrigation for rain-fed crops, and serving as a crucial source for domestic (non-potable) water needs. Many participants highlighted their vital role in sustaining livelihoods, particularly during prolonged dry spells, and their contribution to increasing local groundwater levels, which supports nearby open wells.
- **Challenges in TWHS Management:** Frequent mentions were made of heavy siltation, which significantly reduces the storage capacity of *nadis* and *johads*. Encroachment on catchment areas by agricultural expansion or informal settlements was also a major concern. A noticeable decline in collective action and traditional community-based management institutions was reported, often attributed to out-migration of youth and an increased, albeit often unsustainable, reliance on deep borewells for water access. Water quality degradation due to pollution or lack of maintenance was also a significant concern.
- **Perceptions of Climate Change:** Communities articulated clear observations of changes in local rainfall patterns, including increased intensity of rainfall events, shorter monsoon durations, and more frequent and prolonged dry spells between rainy periods. These changes were directly linked by the communities to decreased water availability and reduced filling frequency of

their traditional water harvesting structures.
- **Willingness to Participate in Revival/Management:** There was a strong expressed willingness among community members to contribute labor (*shramdaan*) for desilting and maintenance activities, especially if government support or clear, tangible benefits were assured. A high level of interest was also noted in forming or strengthening local Water User Associations (WUAs) to ensure equitable management and sustainable operation of TWHS.

E.3. Sample Field Survey Instrument (Questionnaire/Interview Guide Headings):

The following are the key sections and headings from the field survey instrument (questionnaire/interview guide) used during community consultations:

- **General Information:** Date of Interview, Village Name, Block/Tehsil, Respondent Demographics (Age, Gender, Occupation, Role in Community).
- **TWHS Characteristics:** Type of TWHS (Nadi, Johad, Tanka, etc.), Approximate Age/Year of Construction, Ownership (Community, Private, Government), Current Physical Condition (Visual assessment: Good, Fair, Poor, Dysfunctional), Observed Siltation Level, Presence of Encroachment.
- **Water Use Patterns:** Primary Uses of the TWHS (Drinking, Livestock, Irrigation, Domestic, Groundwater Recharge), Seasonal Variation in Water Availability and Use, Number of Households/Livestock Dependent on the TWHS.
- **Management and Maintenance Practices:** Who Manages/Maintains the TWHS (Community, Panchayat, Individual, NGO, Government), Frequency and Type of Maintenance Activities (Desilting, Embankment Repair, Spillway Clearing), Sources of Funding/Labor for Maintenance, Challenges in Management.
- **Perceived Benefits and Impacts:** Perceived Benefits of the TWHS (e.g., increased water availability, improved crop yields, livestock health, reduced migration, ecological benefits), Perceived Impacts on Local Groundwater Levels, Socio-economic Impacts on Livelihoods.
- **Observed Changes and Climate Perceptions:** Observations on Changes in Rainfall Patterns (Intensity, Duration, Frequency), Changes in Temperature, Observed Changes in Water Levels/Filling Frequency of TWHS, Experience with Extreme Weather Events (Droughts, Floods).
- **Challenges and Needs:** Major Challenges Faced by the TWHS (e.g., Siltation, Encroachment, Lack of Funds, Governance Issues), Specific Needs for Rehabilitation or Improvement, Barriers to Collective Action.
- **Willingness to Participate:** Willingness to Contribute Labor (*shramdaan*) for Maintenance, Willingness to Contribute Financially, Interest in Forming/Joining Water User Associations, Interest in Decision-Making Processes.
- **Suggestions for Improvement:** Technical Suggestions (e.g., design modifications, new technologies), Social/Management Suggestions (e.g., strengthening community groups), Policy Suggestions (e.g., government support, legal frameworks).