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Mathematical Analysis Of Sustainable Water Conservation In Dadra And Nagar Haveli Using SCS-CN And GIS Fuzzy Modelling

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ABSTRACT

The diminishing availability of water, coupled with a rising demand for this critical resource, presents a significant challenge. This research focuses on pinpointing ideal locations for water conservation interventions within Dadra and Nagar Haveli (DNH), a tribal-majority Union Territory in western India, by leveraging geospatial techniques. DNH experiences seasonal water deficits, even with 2000–2500 mm of annual rainfall, primarily because of high runoff, poor soil infiltration, and insufficient conservation infrastructure. This research employs the Soil Conservation Service–Curve Number (SCS-CN) model within a GIS environment to prioritize locations for structures such as check dams, percolation ponds, farm ponds, and contour bunds. Using thematic layers derived from a DEM, Landsat 8 imagery, LULC classifications, soil data, and recent (2020-2024) rainfall records, a weighted overlay analysis produced a Water Conservation Potential Index (WCPI). The findings delineate zones that are most suitable for either surface water harvesting or groundwater recharge, supporting targeted, data-driven interventions. The resulting framework offers a practical tool for policymakers to optimize water resource planning in DNH.

Keywords: Geographic Information System (GIS), Runoff potential zones, SCS-CN method, Fuzzy Modelling, Water Conservation Potential Index (WCPI).

1. Introduction

Water scarcity and food security represent two of the most significant global challenges of the 21st century, as water is a foundational resource for life. In nations like India, these issues are compounded by high population density, erratic rainfall, unplanned land-use changes, and sub-optimal water management. Dadra and Nagar Haveli (DNH), a tribal-dominated Union Territory, is a clear example of this paradox. Even with substantial annual rainfall (~2000–2500 mm), it suffers from seasonal water deficits stemming from high runoff volumes, poor soil infiltration, and a shortage of effective conservation infrastructure.

Water availability in DNH has diminished due to a combination of factors, including shifts in land use/land cover (LULC), pronounced slope-driven runoff, and increasing urbanization. As agriculture is a primary livelihood, regional agricultural output relies heavily on successful water storage and conservation measures.

Interventions like check dams, farm ponds, percolation ponds, and contour bunding are established methods for enhancing groundwater recharge and mitigating surface runoff. While conventional site selection methods are limited by subjectivity and scale, Geoinformatics-based approaches using GIS and remote sensing provide superior advantages for identifying potential conservation zones.

The Soil Conservation Service–Curve Number (SCS-CN) model [1] is a standard tool in this field, used for estimating runoff potential based on soil type, land use, and moisture conditions. This model facilitates the calculation of a Water Conservation Potential Index (WCPI) [4], a metric used to prioritize areas for intervention.

Although similar methodologies have been applied elsewhere in India [5, 6, 7], a specific research gap exists for DNH. No comprehensive geospatial study has been conducted to identify site-specific conservation structures in this region. Consequently, this research seeks to:

- Pinpoint runoff-prone areas based on topographic and land-use characteristics;
- Utilize the SCS-CN model to quantify surface runoff;
- Generate a Water Conservation Potential Index (WCPI) map;
- Propose optimal locations for farm ponds, check dams, and percolation ponds;
- Provide evidence-based support for sustainable water management policies in DNH.

2. Overview of the Study Region

This research focuses on Dadra and Nagar Haveli (DNH), a Union Territory in western India situated between approximately $20^0 00'$to $20^0 25'$N latitude and $72^0 50'$ to $73^0 15'$E longitude. The territory covers approximately 491 km² and has a predominantly rural and tribal demographic. Its terrain is marked by undulating topography, with elevations spanning from 30 to 300 meters above mean sea level.

The Daman Ganga River and its tributaries (such as the Sakartod, Piparia, and Vasona) form the region's main dendritic drainage network. Runoff intensity is high, particularly in areas with steep slopes and sparse vegetation, leading to significant water loss during monsoon events.

The geology of DNH consists mainly of Deccan basaltic formations with weathered topsoils. Loamy and lateritic soils are predominant in the cultivable areas [8]. The region has a tropical monsoon climate, with a pronounced wet season (June–September). Annual rainfall averages between 2000 mm and 2500 mm, concentrated heavily in July and August.

Notwithstanding this high level of precipitation, DNH confronts severe seasonal water shortages. This situation highlights the critical need for scientifically identifying optimal water conservation zones through modern geospatial analysis

Study Area Map

3. Data Source and Methodology

The methodology for this study involves the integration of Remote Sensing (RS), Geographic Information System (GIS) techniques, and the SCS-CN hydrological model to pinpoint ideal locations for water conservation structures in DNH, using data from 2020–2024.

3.1. Data Used

- **Satellite Data:** Landsat 8 OLI/TIRS imagery (2020, 2022, 2024) from the USGS Earth Explorer portal [10].
- **Topography:** 30m ASTER Global Digital Elevation Model (DEM) used for deriving topographic parameters [9].
- **Soils:** Soil texture information from the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) [8], classified into Hydrologic Soil Groups (HSG: A, B, C, D).
- **Rainfall:** 2020–2024 daily and monthly data from the IMD (Silvassa) and State Agriculture Department, covering four stations.
- **Basemaps:** Administrative boundaries (village, taluka), road networks, and settlement data from the ISRO Bhuvan Portal and Census 2021.

3.2. Methodology

1. **LULC Classification:** A Supervised Classification (using the Maximum Likelihood Classifier - MLC) was performed in ERDAS IMAGINE on the Landsat 8 imagery. This produced six LULC classes: Agriculture, Degraded Forest, Fallow Land, Forest, Settlement, and Water Bodies.
2. Rainfall Interpolation: The Thiessen Polygon method was used in ArcGIS to create a spatially interpolated mean areal precipitation map from the four station-based rainfall data points [2]. The calculation is a weighted average:

$$P = \sum_{i=1}^{M} P_i W_i$$

where (P) is the mean areal precipitation, (M) is the station count (P_i,) is precipitation at station i, and (W_i) is the area-based weight of its polygon.

3. **Topographic Analysis:** The ASTER DEM [9] was processed to generate maps for slope, flow direction, and flow accumulation. The resulting drainage network was ordered using Strahler's method.
4. Hydrological Modeling (SCS-CN): Surface runoff (Q) was calculated using the SCS-CN model [1]. Curve Numbers (CN) were assigned based on the intersection of LULC and HSG layers. The model's formulas are:

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)}$$

where,

$$S = \frac{25400}{CN} - 254$$

(Q = runoff depth, P = precipitation, S = potential maximum retention).

4. Results and Discussion

4.1. Water Conservation Potential Index (WCPI) Analysis

The study produced a **Water Conservation Potential Index (WCPI)** by applying **Multi-Criteria Decision Analysis (MCDA)** in a GIS environment [4]. This weighted overlay model was built on two key environmental factors:

- **Runoff Coefficient (RC):** The fraction of rainfall that becomes surface runoff.
- **Slope (SL):** The terrain's steepness.

The WCPI was calculated using a linear combination formula:

$$WCPI = (RC_w \times RC_r) + (SL_w \times SL_r)$$

Table No:1: *Water Conservation Potential Index (WCPI) Analysis*

Component	**Description**	**Assigned Value**
$WCPI$	Water Conservation Potential Index	Result
RC_w	Weight for Runoff Coefficient	60% (0.60)
RC_r	Rank for Runoff Coefficient class	1 (least) to 10 (most favorable)
SL_w	Weight for Slope	40% (0.40)
SL_r	Rank for Slope class	1 (least) to 10 (most favorable)

A higher weight (60%) was assigned to the Runoff Coefficient, identifying it as the dominant controlling factor for water retention in this area. A rank of 10 signified the highest potential for conservation (e.g., gentle slopes, low runoff).

4.2. Role of Fuzzy Modelling and Site Suitability

While the SCS-CN method provides runoff estimates, **Fuzzy Modelling** [3] was incorporated to manage the inherent uncertainty and ambiguity in classifying spatial data (e.g., "moderately suitable" slopes).

Key criteria for the Fuzzy Inference System (FIS) [7] included:

1. **Hydrological & Physical Criteria:**
   - **Runoff Potential (SCS-CN):** High runoff indicates more available water for capture.
   - **Slope (DEM):** Gentle slopes (<15%) are preferable for construction and infiltration.
   - **Soil Texture:** Moderately impermeable soils (e.g., Clay Loam) are best for surface water retention.
   - **LULC:** Barren or wastelands are ideal for construction, minimizing agricultural impact.
2. **Proximity & Socio-Economic Criteria (Soft Constraints):**
   - **Distance from Drainage:** Proximity to drainage is vital for in-stream structures like check dams.
   - **Distance from Settlements:** Proximity to villages ensures easy access to the stored water.
   - **Lineament/Fracture Density:** High density is a strong indicator for successful **groundwater recharge** via percolation tanks.

4.3. Geospatial Layers and Zoning

The modeling process produced key geospatial datasets (Soil, Slope, LULC, Runoff Coefficient). The final Runoff Potential Map categorizes the region, guiding the selection of appropriate conservation measures.

Table No:2- Geospatial Layers and Zoning

Runoff Potential Zone	**Implication for Runoff (Q)**	**Recommended Conservation Measure**
Very High	Highest Runoff Volume	**Surface Water Harvesting:** Check Dams, Nala Bunds, Weirs.
Moderate	Moderate Runoff Volume	**Medium-Scale Harvesting:** Farm Ponds, Gully Plugs.
Low	Lowest Runoff Volume	**Groundwater Recharge:** Percolation Tanks, Recharge Pits.

This process enabled the identification of two distinct strategic zones:

1. **Surface Water Harvesting Zones:** These areas show high runoff generation, moderate slopes, and proximity to the drainage network, making them suitable for check dams and farm ponds [6].
2. **Groundwater Recharge Zones:** These locations are defined by low runoff, gentle slopes, and favorable geology (like high lineament density), making them ideal for Percolation Tanks and Recharge Pits [7].

This comprehensive analysis provides a clear spatial distinction between areas best suited for Groundwater Recharge and those ideal for Surface Water Harvesting.

5. Conclusion: Strategic Water Conservation Zoning

This analysis delivers a scientific and spatially-defined foundation for executing sustainable water conservation strategies in Dadra and Nagar Haveli. By progressing from basic land classification to a more sophisticated, integrated approach combining hydrological modeling (SCS-CN) [1, 6] and decision support (Fuzzy Logic) [3, 7], this research attained high-precision suitability mapping**.**

Key Findings and Implications:

- **Dual-Zone Identification:** The primary conclusion is the clear distinction between two high-priority conservation areas: one for Surface Water Harvesting (capturing runoff) and one for Groundwater Recharge (enhancing infiltration).
- **Optimized Resource Use:** The **WCPI Map** facilitates a shift from generic planning to targeted**,** site-specific interventions. This ensures that financial and physical resources are concentrated in locations yielding the highest ecological and socio-economic benefits.
- **Management Database:** The resulting geospatial data (Slope, HSG, LULC, Runoff Potential) [8, 9, 10] create a strong digital database for the local administration, crucial for monitoring, future planning, and adapting to developmental needs.

In summary, this research concludes that effective water management in DNH necessitates a focused, dual-pronged strategy guided by these suitability maps to ensure both immediate water availability and long-term aquifer sustainability.

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