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Assessment of Spatial Variation in Terrain Parameters Impacting Surface and Groundwater Quality for Sustainable Geo-Environmental Management

Kumar R. Rao and A. L. Savitha*

Department of Civil Engineering, R. R. Institute of Technology, Bangalore - 560090, Karnataka, India; savissm@gmail.com

Abstract

Soil and water conservation measures crucial for quality enhancement should focus on terrain-specific challenges. Evaluating groundwater resources from wells in the area is essential to ascertain their appropriateness for different applications. In semi-arid tropical regions, the risk of inland salinity can escalate under extreme conditions like droughts and reduced monsoonal rainfall. During droughts, the groundwater table declines, leading to deterioration in groundwater quality, making it unsuitable for consumption, industrial processes, and arboriculture. In this scenario, analysing the spatial variation in water quality parameters becomes crucial for safeguarding environmental geology and effectively managing the geo-environment of impacted regions. Unfavourable geo-environmental conditions can be mitigated by reducing surface and groundwater pollution, sheet erosion, landslides, and land subsidence. Examining the variation in groundwater quality across both spatial and temporal dimensions is necessary to recommend treatments that make groundwater suitable for various uses, including potable purposes. The spatial as well as temporal variations of different water quality parameters, determined through a composite water quality index, can inform land use alterations, resource exploitation without unacceptable consequences, and artificial recharge measures that do not pollute the geo-environment. Enhancing the sustainability of the geo-environment can be achieved by investigating and prioritizing conservation measures and practices. Employing temporal remote sensing alongside related datasets facilitates the assessment of delineated watersheds within the region through the Analytical Hierarchy Process (AHP) Model. This approach is essential for prioritizing watersheds and formulating strategic action plans to sustain a balanced geo-environment.

Keywords: *AHP Model, Conservation, Geo-Environment, Water Quality, Water Quality Index, Sustainability*

1.0 Introduction

The sustainable usage of saline groundwater resources presents a considerable environmental challenge, as it can lead to the deterioration of water quality, rendering it partially otherwise completely unfit for drinking, agriculture use, construction utilization, as well as domestic purposes. This situation exacerbates the shortage of clean groundwater and adversely impacts geo-environmental circumstances. In the semi-arid Jayamangali watershed, located in Parigi Mandal, Andhra Pradesh, India, research has been conducted to identify the factors contributing to groundwater salinity. Both surface and groundwater quality are compromised by factors such as runoff potential, soil erosion, and human activities. As a result, a comprehensive scientific impost of groundwater quality is essential to develop effective action plans and interventions aimed at improving water quality. These interventions include implementing water

*Author for correspondence

as well as soil conservation measures designed to reduce runoff potential, minimize soil erosion, and decrease the concentration of Total Suspended Solids (TSS) in surface water. This, in turn, enhances groundwater recharge over improved infiltration, ultimately improving overall groundwater quality. Assessing the appropriateness of sites for watershed-based conservation measures involves quantifying factors like surface runoff potential using the Soil Conservation Service (SCS) approach, supported by remotely sensed data[1]. Land use, land cover pattern, and land management practices within the watershed significantly influence runoff potential[2]. Additionally, factors such as soil moisture levels during rainfall (antecedent soil moisture), soil type, and topographic features—including watershed characteristics-affect infiltration and runoff potential[3]. Soil erosion latent as well as slope are also crucial factors that impact water quality, making them vital considerations for identifying optimal sites for conservation efforts[4]. A slope map can be generated using a Digital Elevation Model (DEM), and spatial variations in soil erosion potential can be mapped using soil erosion models[5]. By integrating slope, runoff potential, and soil erosion data in alignment with the criteria established by the Integrated Mission for Sustainable Development (IMSD), suitable sites for various soil and water conservation measures can be identified[6]. Assessing the consistency of these conservation sites through the AHP Model, incorporating temporal studies, can significantly enhance bearable progressible efforts.

2.0 Study Area

The Jayamangali watershed, located between 13°54'0" N and 77°28'60" E, with its UTM position at GR63 and Joint Operation Graphics reference at ND43-12, serves as a representative case for groundwater salinization. A comprehensive analysis of the region provides insights into several topographic as well as runoff factors accountable for the inland salinization of groundwater. A detailed quantitative analysis, using groundwater quality data collected from wells throughout the area, examines groundwater quality signs, nutrients, physical constraints, inorganic non-metals, as well as trace metals in an integrated manner to assess spatial variation. Groundwater underneath agricultural land is particularly vulnerable to reduced quality due to fertilizer application. The degradation of water quality in the wells is increasingly evident as agricultural and urban development expands. Built-up areas too contribute to groundwater contamination. The region's environment deficiencies energy-efficient strategies to preserve comfort, as materials with low thermal capacity as well as conductivity are not used to insulate against heat in hot climatic zones or retain warmth in cold areas. The district receives an average annual rainfall of 1200 mm, primarily during the southwest monsoon season. The standard deviancy of rainfall is 415.8 mm, with a constant of variation ranging from 30 to 35 mm across different years at the rain gauge stations. Figure 1 demonstrates the study area, showcasing the watersheds and conservation efforts, and highlights the designated sites for various hydrological preservation measures determined over integrated analysis.

3.0 Methodology

The level-1 land cover assessment offers comprehensive details on various topographies such as built-up areas, streams, water bodies, as well as the necessary conservation measures needed to maintain a balanced geo-environment. Within this framework, land cover data plays a crucial role in applying the Soil Conservation Service model to assessment of runoff potential and evaluate site suitability for conservation initiatives[7]. These efforts help improve surface water quality, boost groundwater resources, and support the development of a healthier river ecosystem. Given the region's high runoff potential, strategic planning of conservation measures, in alignment with the Integrated Mission for Sustainable Development (IMSD), is essential. Soil erosion potential remained analysed using specific erosion models, while slope information was derived from a Digital Elevation Model. The accuracy of GIS-recommended conservation sites was validated through field inspections. Hydrological conservation structures were strategically located near rivulets to confirm adequate water accessibility then were placed away from built-up areas to reduce environmental impacts and prevent conflicts with conservation efforts[8]. The Analytical Hierarchy Process was utilized to ascribe pairwise weights to the selected criteria, followed by the construction of a pairwise comparison matrix and

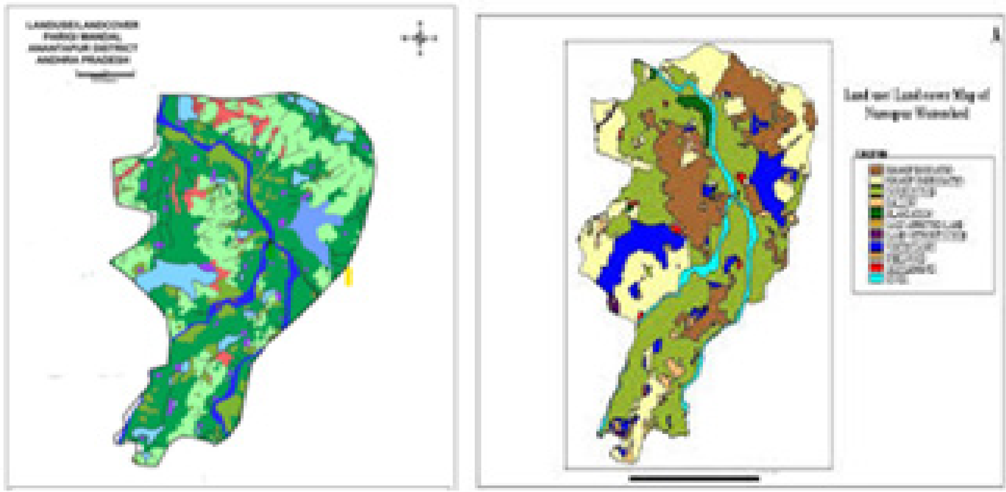

Figure 1. Study area, highlighting the various watersheds and the associated conservation efforts.

Table 1. Factors for determining the suitability of conservation site locations

Sl.No.	Type of Conservation	Run off Potential	Slope	Soil Erosion potential
1	Contour Bund	Medium	Low	High
2	Gully Plug	High	Medium	Low
3	Stream bunds	Medium	Low	Medium
4	Farm Pond	High	Low	High
1	Contour Bund	Medium	Low	High

the calculation of conforming normalized weights. Subsequently, multi-criteria weights were assigned to individually criterion based on the magnitude of changes observed over the selected time period. The Sustainability Index for each criterion across all watersheds in the region was then computed using Equation 1.

(EIk) = Σ (Weight obtained for the K^{th} criteria in the J^{th} Watershed x Reduction/Increase of K^{th} criteria for J^{th} Watershed/ (Area of J^{th} Watershed) (1)

Where K varies from 1 to n and J from 1 to m, the CSI was determined using Equation 2. This provided a measurable evaluation of how effective preservation efforts were across various watersheds. The CSI serves as a key metric for ranking watersheds and creating targeted action plans to support their defensible development[9]. The CSI assessment represents the relative significance of each selected criterion, offering essential insights for prioritizing and implementing conservation strategies.

CSI = EI-1*W1+EI-2*W2+EI-3*W3+EI-4*W4+EI-5*W5 (2)

In this equation, W1, W2, and W5 denote the pairwise weights assigned by the Analytical Hierarchy Process (AHP) to the five selected criteria, while EI-1, EI-2, ..., EI-5 represents the sustainability indices corresponding to these criteria. Higher CSI values indicate better sustainability outcomes within the watersheds[10]. An analysis was conducted on eight delineated watersheds, which included proposed conservation sites. This analysis utilized AHP modelling over a five-year period, from February 2016 to January 2021, with the support of Remote

Sensing LISS-III data. The purpose of this analysis was to create a CSI to measure conservational sustainability across the 5 selected criteria, serving as an essential tool for evaluating the effectiveness of the proposed conservation measures. The multi-criteria analysis cantered on the subsequent 5 criteria for AHP evaluation: (a) Growth in cultivable land area (C-1), (b) Decline in deteriorated zones (C-2), (c) Mitigation of soil erosion risk (C-3), (d) Lowering of runoff capacity (C-4), and (e) Decrease in terrain roughness index (C-5), a morphological metric. Conservation efforts were strategically positioned near watercourses to guarantee adequate water supply and were situated away from urbanized regions to reduce environmental consequences. Variations in topographic and hydrological conditions play a significant role in environmental sustainability by supporting water conservation efforts, which in turn, enhance groundwater availability and quality. The success of these proposed conservation sites in achieving sustainable development depends on the productive changes within the watersheds, brought about by the phased implementation of the recommended conservation measures. An evaluation utilizing an Analytic Hierarchy Process (AHP) model can be conducted on the watersheds within the study area, focusing on a defined time frame anticipated to experience significant landscape alterations. These changes may impact the watersheds' attributes. The AHP model's outcomes during this period will generate estimates of the Composite Sustainability Index (CSI) for each watershed. This index acts as a measure of the degree of sustainable development achieved, facilitating the prioritization of watersheds based on their CSI scores for subsequent phased development. The goal is to enhance water quality and foster a sustainable geo-environment. A flowchart depicting the methodology is provided in Figure 2.

4.0 Results and Discussion

A comprehensive assessment of groundwater quality variations is essential for geo-environmental development

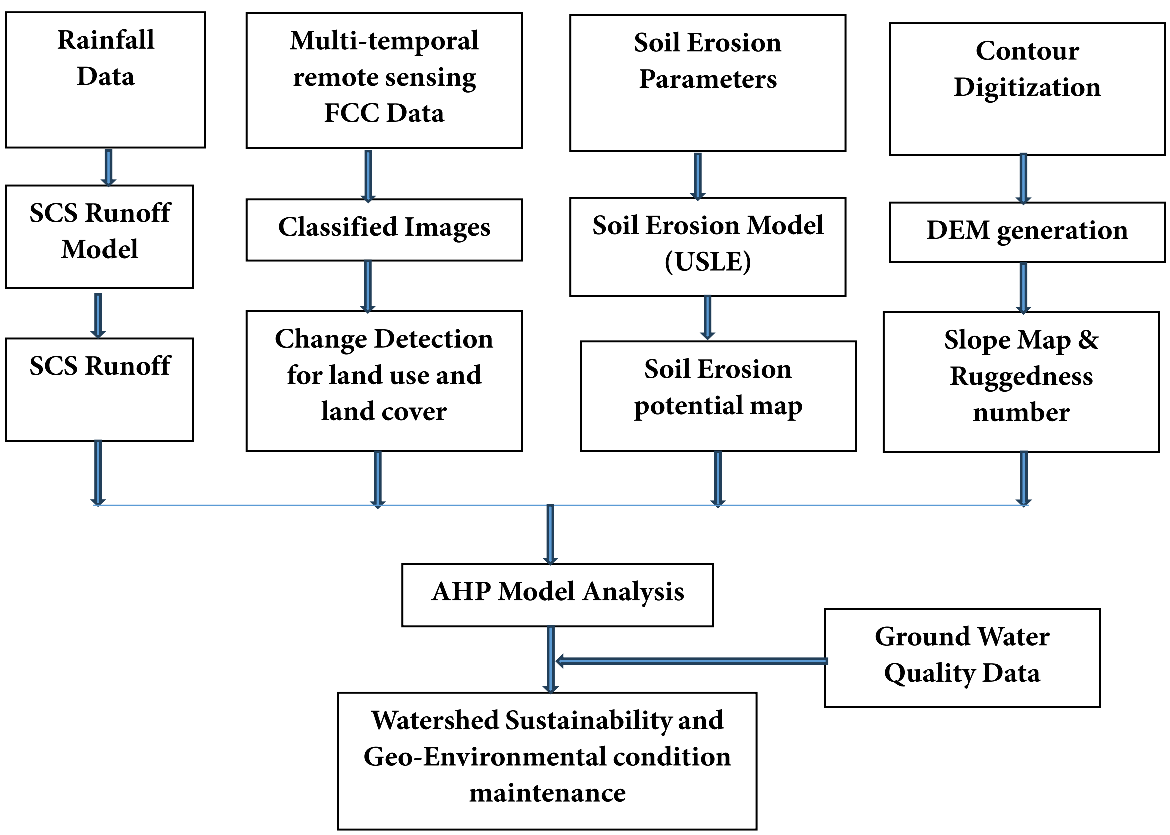

Figure 2. Flowchart of the methodology.

to identify any instances where water quality parameters exceed permissible limits. Such assessments are crucial for identifying the underlying factors contributing to these variations. In this context, analyzing spatial variations is vital for understanding the causes of water quality decline and developing appropriate action plans, including evaluating site suitability for conservation measures aimed at improving both surface and groundwater quality. Consequently, a site suitability analysis for conservation interventions was performed after evaluating runoff potential, soil erosion potential, and slope variations in the region.

Table 2 presents the values for parameters such as runoff, runoff potential, and morphological characteristics across the eight delineated watersheds. The area has a runoff potential exceeding 0.85, indicating extremely high levels. The heightened runoff capacity leads to increased sediment accumulation in aquatic systems and intensifies water quality issues, emphasizing the critical need for conservation actions to enhance both surface and groundwater standards. Seasonal variations in groundwater quality are notably influenced by agricultural and domestic activities, particularly through processes of infiltration and percolation during the rainy season. Consequently, groundwater quality in the area is strongly affected by the underlying geology and environmental conditions. Elevated electrical conductivity levels point to high concentrations of dissolved salts, and the water is typically alkaline. Levels of Na^+, K^+, Ca^+, Cl, Mg^+, SO_4^{2-}, and carbonates often exceed the standards established by the Central Pollution Control Board (CPCB). Furthermore, the groundwater contains significant amounts of chromium, cadmium, and other heavy metals, which present serious health hazards.

This context necessitates a detailed examination of all water quality indicators to assess groundwater usability for various applications. Spatial variations in the Composite Ground Quality Index (CGQI) were analyzed using kriging interpolation techniques to map the extent of contamination across different locations. Additionally, water quality parameters were measured at the discharge points of the eight identified watersheds, with the Composite Water Quality Index values documented in Table 3, illustrating pollution levels.

Human activities exert substantial impacts on the physical, chemical, and biological characteristics of water resources, making a rigorous scientific assessment of groundwater quality essential. This assessment should provide a robust foundation for management decisions by continuously monitoring, identifying, and analyzing trends in water quality variations. Human-induced factors can modify the geo-environment, leading to

Table 2. Morphological parameters and SCS runoff depth and rate

Micro Watershed	SCS Runoff (cm)	SCS Peak Runoff (m3/sec)	Runoff Potential	Form Factor	Ruggedness No.	Circulatory ratio	Stream Density
No-1	119.73	3.83	0.89	0.2	2.7	0.32	0.04
No-2	116.28	5.26	0.86	0.4	2.8	0.29	0.03
No-3	118.56	5.42	0.88	0.6	2.1	0.12	0.03
No-4	121.62	4.11	0.90	0.2	1.4	0.3	0.02
No-5	119.45	8	0.89	0.5	1.8	0.47	0.02
No-6	121.33	1.73	0.90	0.6	1.6	0.62	0.02
No-7	119.33	1.75	0.89	0.4	2	0.71	0.03
No-8	117.95	1.97	0.88	0.2	2.2	0.41	0.03

Table 3. Water quality and composite quality index values recorded at the outlets of the eight delineated watersheds

Outlet of WS No	DO (mg/L)	BOD (mg/L)	*E. coli* (cfu/100 ml).	TOC (cfu/100ml)	CQI values for the nine WS
1	8.33	4.24	93	21	5
2	8.08	8.08	105	14	5
3	8.06	7.11	115	31	10
4	6.54	35.24	318	15	18
5	7.81	17.09	80	36	19
6	6.41	25.97	637	18	14
7	6.48	29.6	165	49	15
8	7.23	31.3	118	51	19
9	7.6	22.1	124	18	10
				Mean CQI	12.77

changes in the mineralogical composition of groundwater, potentially decreasing sustainability and creating adverse conditions in India, the development of built environments must prioritize both operational efficiency and construction practices to ensure the sustainability of surface and groundwater resources. Effective planning and implementation on-site are crucial; failure to meet performance expectations can lead to unmet design goals. Environmental sustainability is shaped by topographical and hydrological factors, making the study of spatial variations in these aspects critical for selecting sites for conservation efforts that improve groundwater quantity and quality. Table 4 illustrates the pairwise AHP criteria matrix, showing the relative weights assigned to each criterion based on their significance.

Human activities profoundly affect the physical, chemical, as well as biological properties of water resources, underscoring the need for a thorough scientific evaluation of groundwater quality. This assessment is crucial for providing a strong foundation for management

Table 4. Pair-wise assignment of AHP criteria weights for the five selected criteria

Criteria	C1	C2	C3	C4	C5
C-1	1	1	8	7	8
C-2	1	1	8	8	3
C-3	0.1	0.1	1	3	3
C-4	0.1	0.1	0.3	1	3
C-5	0.1	0.3	0.3	0.3	1

decisions, involving consistent monitoring, identification, and analysis of trends in water quality changes. Human-induced changes can significantly alter the geo-environment, affecting the mineralogical composition of groundwater and potentially reducing sustainability while creating adverse conditions. In India, the development of built environments must take into account both operational performance and the construction phase to ensure sustainability. This approach guarantees that planning commitments are effectively implemented on-site, with the understanding that if the built environment does not perform as intended, it will fail to meet its design objectives. Environmental sustainability is affected by landform and water flow characteristics, making the examination of spatial differences in these factors essential for choosing optimal sites for conservation initiatives aimed at enhancing groundwater quality and quantity. Table 5 presents the pairwise AHP criteria matrix, providing a detailed breakdown of the relative importance assigned to each factor based on their interconnections.

The weights assigned for evaluating temporal changes across the five chosen criteria were determined based on the observed magnitude of changes, with values ranging from one to nine according to the level of variation. These details are outlined in Table 5. After assigning these subjective weights to each criterion for the eight watersheds, the EI-K value for each criterion in the watersheds was computed using Equation 1. The EI-K values, shown in Table 6, were obtained by multiplying the multi-criteria weights (as detailed in Table 5) by the corresponding changes in criterion values per unit area of each watershed. The magnitude of the EI-K values indicates the extent of temporal variations within each watershed over the specified period, with higher values reflecting more significant changes in the criteria. The Composite Sustainability Index (CSI) was then calculated using the EI-K values combined with the relevant AHP weights for each criterion, as detailed in Table 6. The CSI values for the watersheds ranged from 0.0008 to 1.300, representing the overall sustainability level of each watershed. These CSI values, derived from the EI-K values and AHP weights outlined in Table 6, ranged from 0.0008 to 1.300 across the different watersheds. Table 7 provides the CSI values for each watershed and outlines the priority ranking for achieving sustainable development based on these values. Watersheds with higher CSI values are more sustainable and therefore require lower priority for further

Table 5. Multi-criteria parameters and their corresponding weights

Criteria C-1	Criteria C-2	Criteria C-3	Criteria C-4	Criteria C-5
13(8)	20.10(7)	0.017(2)	0.28 (3)	0.000013(7)
11(6)	29.95(9)	0.063(6)	0.33(3)	0.0000113(2)
15(9)	22.50(7)	0.10(1)	0.4(4)	0.0000038(3)
14(8)	18.0(5)	0.09(9)	0.3(3)	0.0000099(4)
16(9)	30.05(9)	0.05(5)	0.18(2)	0.0000078(4)
3.0(2)	14.50(1)	0.03(3)	0.28(3)	0.000012(6)
2.17(1)	18.30(5)	0.06(6)	0.37(4)	0.000011(5)
2.34(2)	19.07(6)	0.03(3)	0.6(6)	0.000015(3)

Table 6. EI_k values for different criteria and for eight watersheds

Water shed No	EI-1	EI-2	EI-3	EI-4	EI-5
1	0.005	0.0068	1.6E-06	4.08E-05	4.4E-09
2	0.0009	0.004	5.7E-06	1.5E-05	3.4E-10
3	0.0034	0.004	2.5E-06	4.06E-05	2.9E-10
4	0.0043	0.0035	3.1E-05	3.52E-05	1.55E-09
5	0.0046	0.008	7.9E-06	1.15E-05	9.9E-10
6	0.00027	0.0006	4.2E-06	3.9E-05	3.35E-09
7	9.02E-05	0.0038	1.5E-05	6.15E-05	2.28E-09
8	8.50E-05	0.002	1.6E-06	6.54E-05	8.17E-10

Table 7. CSI-Index values for eight watersheds

Watershed No	CSI-Values	Priority to be Accorded for Sustainable Development
1	0.005	Average to Moderate
2	0.002	Average
3	0.003	Moderate
4	1.300	Low
5	0.005	Average to Moderate
6	0.004	Moderate
7	0.002	Average
8	0.0008	Very High

development efforts. Conversely, watersheds with lower CSI values indicate reduced sustainability, necessitating a higher priority for implementing conservation measures to promote environmentally sustainable development in these areas.

Spatial variation analysis and the application of the AHP framework are vital for identifying the key issues accountable for the decline in the quality of water. These insights are essential for developing specific action plans aimed at improving sustainability, which will, in turn, lead to better geo-environmental conditions in the area.

5.0 Conclusion

Addressing geo-environmental challenges and improving the riverine ecosystem requires consideration of both terrain-related parameters and water quality factors. This combined approach allows for the identification of optimal sites for water and soil conservation, thereby improving both surface and groundwater resources. The suitability of locations for different watershed conservation activities can be assessed by adhering to established guidelines for each conservation approach. The effectiveness of these locations in achieving sustainable development will hinge on the positive outcomes within the watersheds, which arise from the step-by-step application of conservation techniques. In this regard, utilizing an Analytical Hierarchy Process (AHP) model to assess the watersheds in the study area proves to be particularly advantageous. By concentrating on specific time frames when notable landscape changes are anticipated, the AHP model's findings can be used to compute the Composite Sustainability Index (CSI) for each watershed. This index may be regarded as a measure to ascertain the extent of sustainable development that has taken place and also to prioritize the watersheds based on the CSI values for further phase-wise watershed development to meet the objective.

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