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Geo-Environmental Evaluation and Its Implications for Sustainable Development in the Warana River Basin

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Abstract: *The Warana River Basin, an important tributary of the Krishna River in western India, exhibits varied physiographic, climatic and ecological characteristics that shape its geomorphic and environmental framework. Serving as a crucial region for agriculture, water resources and socio-economic development, the basin has experienced increasing stress due to land-use changes, anthropogenic activities and irregular rainfall patterns. This study analyzes key geo environmental parameters such as elevation, slope, slope aspect, drainage density, soil texture, contour, hillshade and rainfall erosivity to understand their interrelations and impact on basin evolution. Remote Sensing (RS) and Geographic Information System (GIS) techniques were employed to integrate multi-source datasets, including satellite imagery, topographic maps and Digital Elevation Models (DEMs). The basin's geomorphology consists of structural hills, plateaus, pediments and river terraces that influence runoff dynamics, groundwater recharge and agricultural potential. The predominance of dendritic to sub-dendritic drainage patterns indicates lithological control imposed by basaltic formations. Moreover, high monsoonal rainfall intensifies soil erosion and sedimentation, posing challenges to sustainable land and water resource management. The integrated geo environmental evaluation thus provides a scientific basis for watershed prioritization and the formulation of soil and water conservation strategies for sustainable development within the Warana River Basin.*

Keywords: Geomorphology, Remote Sensing, GIS and Watershed prioritization.

1. Introduction:

Sustainable watershed management requires a holistic understanding of geo-environmental parameters that govern landform processes, hydrology, soil dynamics and ecological functioning [1]. The Warana River Basin, located in the semi-humid tropical region of Maharashtra and Karnataka, is an agriculturally productive region supporting sugarcane, cereals, horticulture and extensive rural settlements [2]. Over recent decades, increasing population pressure, intensive cultivation, deforestation, and unplanned land conversion have intensified soil erosion, altered hydrological regimes, and reduced ecological resilience [3].

Geo-environmental evaluation using GIS and Remote Sensing has emerged as a robust approach for characterizing terrain and environmental processes at watershed scale. Maps of elevation, slope, aspect, soil classes and erosivity factors help identify vulnerable zones, resource potentials, and constraints for sustainable development [4].

The study of geo-environmental parameters is crucial to understand the interactions of geology, geomorphology, hydrology, soils, and land use that shape watershed dynamics [5]. Assessing factors like morphometry, drainage, slope, relief, lithology, and land cover provides insights into ecological health, hydrological response, and erosion risks. Such studies support sub-watershed prioritization and sustainable conservation planning [6]. Advancements in geospatial technologies like Remote Sensing (RS) and Geographic Information Systems (GIS) have profoundly enhanced the precision and

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efficiency of analyzing these parameters. They enable comprehensive evaluation of drainage systems, soil distribution, slope gradients, land cover changes and hydrological processes even in difficult-to-access or ungauged watersheds [7].

Geo-environmental analysis is particularly relevant in the context of soil erosion. High-relief basins with sparse vegetation and impermeable soils are more prone to rapid runoff and elevated erosion risk, as morphometric parameters like drainage density and overland flow length directly correlate with erosion potential [8]. In most of the studies, spatial prediction of soil erosion phenomena was investigated successfully considering geophysical attributes such as slope steepness, soil type, length-slope (LS) factor, land use/land cover, geomorphology, elevation, distance from the river, drainage density, relative relief, rainfall erosivity etc.[9].

Studying its geo-environmental parameters is vital to assess geomorphology, soils, hydrology and ecological sensitivity, providing a basis for watershed prioritization, erosion risk assessment, and sustainable management. This study conducts a detailed geo-environmental assessment of the Warana River Basin and analyzes the implications for watershed planning and long-term sustainability.

2. Literature Review:

Remote sensing and GIS-based methodologies used to assess the suitability of various areas within the Warana River Basin for implementing soil and water conservation measures. Their research identified critical zones prone to erosion and areas with high runoff potential, recommending appropriate conservation practices such as contour bunding and check dams. The study provided a spatial framework for prioritizing conservation efforts, aiming to enhance the basin's ecological stability and agricultural productivity [10].

Evaluating morphometric parameters, such as basin relief, linear, and aerial aspects, to understand watershed characteristics are important. These parameters influence hydrological behavior and are crucial for watershed management [11].

Study of Geo-environmental evaluation for exploring potential soil erosion zones explores the use of geo-environmental parameters like lithology, slope and land use in mapping groundwater potential zones. It demonstrates integration of these parameters for effective watershed management and conservation planning [12].

Case studies demonstrate that prioritization based on composite indices (combining R, K, LS, C, P and morphometric factors) effectively ranks sub-watersheds by vulnerability and guides the siting of measures such as contour bunds, check dams and afforestation [4].

3. Study Area:

The River Warana (16° 47' 00"N to 17°15'15" N and 73°30'45" E to 74°30'00" E), a tributary of the River Krishna, begins in the Sahyadri range in Patan Taluka of Satara District, Maharashtra, India, and flows southwest for 160 km. before joining the River Krishna at Haripur near Sangli . In the western part of the Deccan Plateau, the river drains a total area of 2095 sq. km [13]. The eastern part of the basin is less mountainous and has a flat rolling landscape than the western part. The basin is located in the Western Ghats' rain-shadow zone and has a moderate climate. The climate is semi-humid tropical and the rainfall falls rapidly from west to east. It varies from 4000 mm in upper western parts around Sahayadries and Konkan portion and less than 700 mm in the lower eastern portions [14]. Major land use includes sugarcane cultivation, paddy fields, horticulture, forest patches and rural settlements, supported by fertile soils derived from basaltic Deccan Traps. The Warana River and its tributaries form a dendritic drainage pattern contributing significantly to irrigation, groundwater recharge, and agricultural productivity [13]. Rapid land-use change, unregulated extraction of water resources, soil erosion in upper catchments, and deforestation have made the basin environmentally fragile, highlighting the need for integrated geo-environmental evaluation and sustainable watershed management. Fig. 1 depicts the study area’s location map.

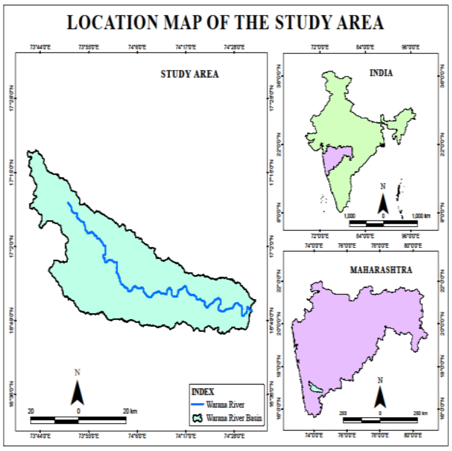

Figure 1: Location Map of Study Area

4. Data and Methodology:

GIS-based processing included DEM generation, slope and aspect derivation, drainage density computation, soil texture integration, contour, hillshade and estimation of rainfall erosivity (R-factor). All layers were overlaid in GIS to analyze spatial patterns and identify erosion-prone zones. This study used SRTM DEM of 30 m resolution. The Warana River Basin was delineated using Survey of India (SOI) topographic sheets and Digital Elevation Model (DEM) data in GIS. GIS and remote sensing techniques used to integrate all datasets to generate thematic maps for slope, aspect, drainage and elevation. Soil texture map is obtained from National bureau of soil survey and land use planning, Nagpur. Slope, Aspect, Elevation analysis, contour and hillshade is derived from DEM to understand terrain characteristics and solar exposure. Rainfall erosivity map is prepared from Maharain rainfall data.

5. Results and Discussion:

5.1 Digital Elevation Model (DEM):

The DEM of the Warana River Basin shown in Fig. 2 shows elevations from 530 m to 1109 m, with high elevations (900–1109 m) in the northwest and southwest, moderate elevations (700–900 m) in the central undulating terrain, and low elevations (530–700 m) in the eastern plains. High-slope areas require soil and water conservation, fertile lowlands suit agriculture, mid- and lower-basin zones need flood management, and hilly terrain is best reserved for forests and plantations.

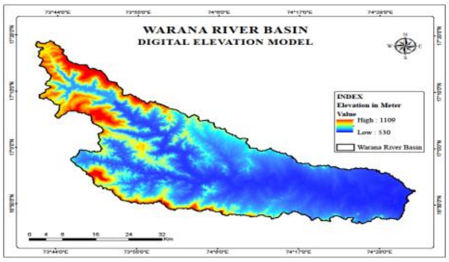

Figure 2: DEM Map of Warana River Basin

5.2 Slope Analysis:

Fig. 3 represents Spatial Distribution of slope map shows that low slope areas (0–5%) occurs mostly in the eastern and southeastern parts of the basin. These are broad plains and valley floors where the main river channel flows. Moderate slopes (5–10%) spread across the central basin, marking transitional zones from uplands to plains. These areas support mixed land use agriculture with some soil and water conservation measures.

Slope map of Warana River Basin also shows Strong to moderately steep slopes (10–35%) which is concentrated in the western, northwestern and southwestern basin margins. This area is associated with hill slopes, forest cover and higher erosion risk**.** Very steep slopes (>35%) found in isolated patches in upland and escarpment regions**.** These area of very steep slope is highly prone to soil erosion, landslides and unsuitable for agriculture. This slope variation in the river basin governs hydrology, erosion potential, land use, and soil-water conservation strategies. Proper management of steep uplands and utilization of gentle slopes for agriculture can enhance sustainability of the basin.

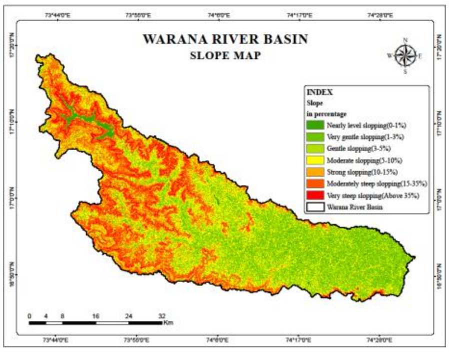

Figure 3: Slope Map of Warana River Basin

5.3 Slope Aspect:

The aspect map of the Warana River Basin shown in Fig. 4 explains south and southwest facing slopes, which receive more sunlight, causing high evapotranspiration, low soil moisture and greater erosion risk. North and northeast facing slopes are cooler, moist and vegetation rich. East-facing slopes maintain balanced moisture and favorable for farming. Sun-facing western uplands need afforestation and soil conservation, whereas eastern plains and north slopes support agriculture and water retention.

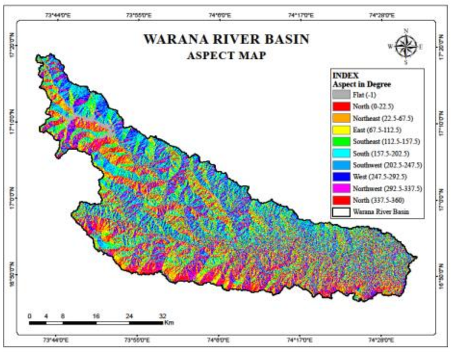

Figure 4: Aspect Map of Warana River Basin

5.4 Drainage Density:

The drainage density map of the Warana River Basin shows very high density in the steep western and central highlands, indicating strong dissection and high erosion risk. Medium density occurs in transitional zones, while low density dominates the eastern plains, reflecting gentle slopes, permeable soils and good recharge potential. Study of hydrological implications of the drainage density map explains that high to very high Drainage Density areas receive quick stormflow response, risk of flash floods and high erosion. These areas are best suited for forest conservation, check dams and erosion control measures**.** The drainage Density map of Warana river basin is shown in Fig. 5.

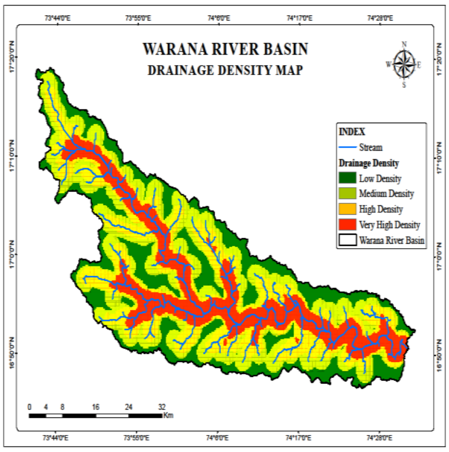

Figure 5: Drainage Density Map of Warana River Basin

5.5 Soil Texture:

Fig. 6 shows various soil texture categories of Warana river basin. Extremely shallow soils and very shallow loamy soils are found in upper catchment area i.e. in Western Ghats section. These soils are thin, less fertile, and highly prone to erosion due to steep slopes and heavy rainfall. In central part of basin i.e. in middle catchment, moderately deep to deep, well-drained loamy and clayey soils are found. These soils have moderate fertility, supporting rainfed crops. These soils are suitable for cereals, pulses and horticultural crops under rainfed conditions. Well-drained fine and clayey soils occurs in lower catchment i.e. eastern plains near Krishna confluence. These are fertile black soils highly suitable for water-intensive crops like sugarcane, cotton, and cereals.

The Warana River Basin shows strong spatial variation in soils ranging from extremely shallow and erosion-prone soils in the upper Ghats to deep, fertile black soils in the lower plains. This variation directly influences agricultural practices, erosion risk and water management challenges. Conservation measures in the upper catchments and sustainable agriculture in the lower basin are crucial for the long-term environmental stability of the basin.

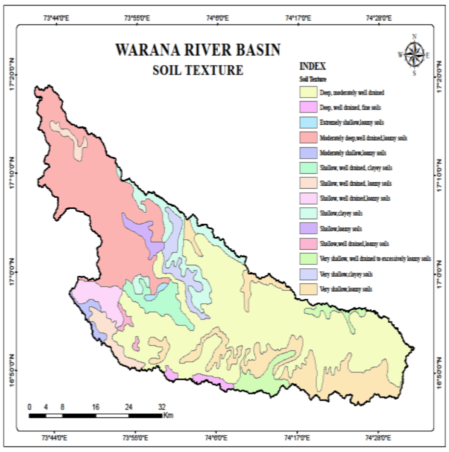

Figure 6: Soil Texture Map of Warana River Basin

5.6 Contour:

The elevation and relief features of the Warana River Basin are depicted on the contour map in Figure 7. Contours are lines of equal elevation that show the influence of drainage patterns, slope variations, and terrain undulations [15]. High relief and steep slopes are indicated by the tightly packed contours in the upper watershed and the northwest. These regions are very vulnerable to soil erosion and runoff. The central basin, which depicts undulating topography with mild to moderate slopes, has moderately spaced contours. The Lower Basin's gradual slope and abundant alluvial soils make it ideal for intensive agriculture, where products like sugarcane, cereals and paddy can be cultivated. To ensure long-term agricultural sustainability, effective irrigation techniques and flood control should be prioritized.

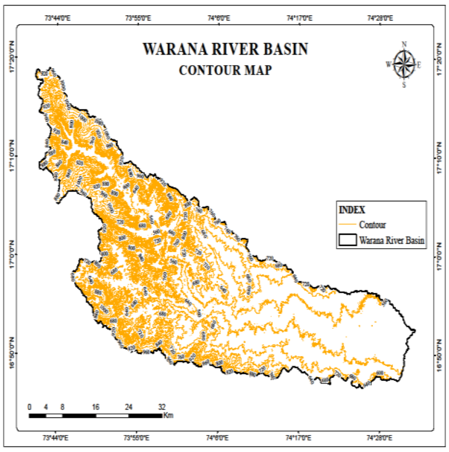

Figure 7: Contour map of Warana River Basin

5.7 Hillshade:

Fig. 8 shows hillshade map of Warana river basin. Topographic representation of hillshade map states that the hillshade map is a 3D visualization created by simulating sunlight over the terrain, where darker areas represent shaded slopes and lighter areas represent illuminated slopes. The central portion of river basin shows a mix of dissected uplands and rolling terrain. The eastern part of the basin is comparatively smooth and flat with gentle slopes. These are depositional plains formed by alluvial processes of the Warana River and its tributaries.

The hillshade map of the Warana River Basin effectively highlights the contrast between rugged, erosion-prone highlands in the west and fertile, agriculturally productive plains in the east**.** It provides critical insights for watershed management, flood control, soil conservation and agricultural planning.

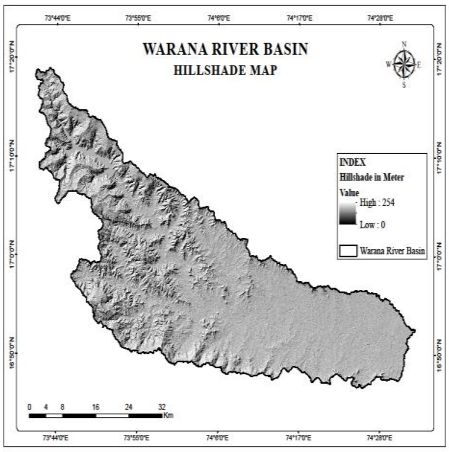

Figure 8: Hillshade map of Warana River Basin

5.8 Rainfall Erosivity:

The rainfall erosivity map of the Warana River Basin shown in fig. 9 depicts the spatial distribution of the basin's potential for rainfall induced soil erosion, derived from long-term precipitation patterns. The map shows a clear west-to-east gradient, with higher erosivity values concentrated in the western and south-western parts of the basin, where the R-factor reaches approximately 363 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$. This zone corresponds to the Western Ghats foothill region, which receives intense and prolonged monsoonal rainfall, resulting in greater kinetic energy of raindrop impact and higher runoff generation. The central and eastern parts of the basin exhibit lower erosivity values i.e. 214 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$ due to relatively reduced rainfall intensity and shorter duration of monsoon events.

The rainfall erosivity map highlights the need for site-specific soil and water conservation measures, especially in the western part of the basin where erosive forces are strongest.

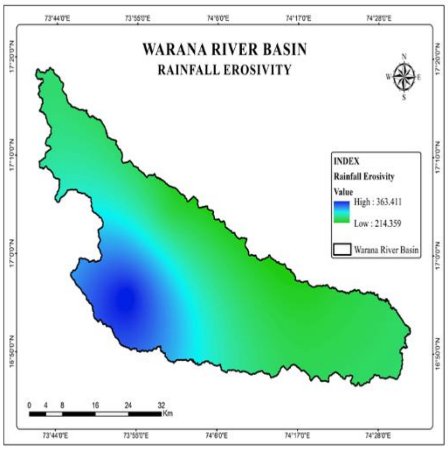

Figure 9: Rainfall Erosivity map of Warana River Basin

6. Geo-Environmental Implications for Sustainable Development

The integrated analysis of geo-environmental parameters of the Warana River Basin such as elevation, slope, slope aspect, drainage density, soil texture, contour patterns, hillshade characteristics and rainfall erosivity reveals critical implications for sustainable development planning across the watershed. In order to stabilize slopes and improve soil retention, interventions like contour bunding, terracing, afforestation and gully control are necessary. The DEM, slope, and contour maps together highlight steep, rugged western uplands that are extremely vulnerable to runoff, soil erosion and land degradation.

The aspect map emphasizes that south- and southwest-facing slopes experience higher radiation and evapotranspiration, increasing moisture stress and erosion susceptibility, thus requiring vegetation-based soil conservation. High drainage density zones identified in the western and central highlands indicates rapid runoff and intense dissection, demanding priority watershed treatment to reduce sediment yield. Soil texture distribution shows shallow, erosion-prone soils in upper catchments, medium-depth loamy soils in mid-basin transition zones, and fertile clayey soils in the lower plains shows the need for differential land-use strategies that limit disturbance in fragile uplands while promoting sustainable agriculture and efficient irrigation in the plains. The hillshade map reinforces the contrast between erosion-prone highlands and depositional plains, guiding location-specific agricultural and conservation planning. Finally, the rainfall erosivity map demonstrates strong erosive forces in the western basin due to high-intensity monsoon rainfall, which amplifies soil detachment and downstream sedimentation. These geo-environmental insights provide a scientific base for watershed prioritization, climate-resilient agriculture, sustainable land-use zoning and long-term ecological management essential for ensuring the sustainable development of the Warana River Basin.

7. Conclusion:

The geo-environmental evaluation of the Warana River Basin demonstrates that variations in terrain, soil characteristics, drainage patterns and rainfall intensity strongly influence the basin's erosion vulnerability and resource potential. The integrated GIS-based analysis identifies the western highlands as highly erosion-prone due to steep slopes, high drainage density and strong rainfall erosivity, while the central and eastern plains offer greater suitability for agriculture and groundwater recharge. These findings highlight the need for location-specific soil and water conservation measures, sustainable land-use planning and watershed-based management strategies to enhance ecological stability and support long-term socio-economic development in the basin.

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