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Morphometric watershed prioritization for sustainable agriculture and water management on Santa Cruz island, galápagos

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ABSTRACT

Efficient water management is essential for agricultural sustainability, especially on islands where freshwater resources are limited and vulnerable. On Santa Cruz Island (Galápagos, Ecuador), the majority of the water supply originates from underground aquifers that face threats such as saltwater intrusion, contamination, and increasing agricultural and urban demand. This study aims to identify and prioritize watersheds with favorable conditions for sustainable water management focused on agriculture. A morphometric analysis of 24 watersheds was conducted, assessing characteristics such as shape, relief, and linear features to estimate erosion vulnerability and water availability. The results enabled classification of watersheds according to their potential for water conservation and agricultural use. Five priority watersheds (SW15, SW22, SW19, SW1, and SW14) were identified as having favorable conditions for water retention and sustainable agricultural practices. Other watersheds with higher erosion susceptibility require conservation measures to prevent soil degradation. This prioritization serves as a practical tool to focus efforts and resources on the most suitable areas for water management and sustainable agricultural development on the island. Overall, the study supports strategic planning to strengthen resilience against water scarcity and climate change in volcanic island environments.

1. Introduction

Sustainable management of water resources remains one of the most critical global challenges, due to its essential role in supporting human well-being, ecosystem stability, and productive activities, particularly agriculture, which heavily relies on water availability and quality (UNESCO, 2022; Qi et al., 2025). As demand continues to grow (driven by population growth and increasing pressure from various productive sectors), this challenge is further complicated by variability in global precipitation patterns (Li et al., 2021; WMO, 2025). Effectively addressing these complex dynamics requires proactive, integrated, and multi-sectoral approaches to water resources management.

To understand and manage water resources effectively, it is essential to distinguish between their primary sources. A fundamental distinction in hydrological studies is made between surface water and groundwater systems, both vital components of the hydrological cycle (Salako and Adepelumi, 2018). Some precipitation flows overland, forming rivers and streams, known as surface runoff, while another portion infiltrates the soil, saturates pores and fractures, and moves under gravity towards springs, rivers, or the ocean, constituting groundwater flow (Fuentes, 1992; Li and Liu, 2019; Water Science School, 2019). Groundwater, stored in underground aquifers, represents the main accessible freshwater reservoir on Earth and plays a crucial role in sustaining terrestrial and aquatic ecosystems (Aranguren-Díaz et al., 2024). According to Shiklomanov and Rodda (2003), citing Garmonov's estimate (Korzun, 1974), the planet's total freshwater volume is approximately 10.6 million km^3, of which 99 % is groundwater (Dalin et al., 2019; UNESCO, 2022). This distinction becomes particularly relevant when comparing continental and insular hydrological dynamics. While aquifers in continental regions often have limited interaction with saline water, volcanic islands are especially vulnerable to rapid groundwater depletion and saltwater intrusion due to excessive extraction (Falkland, 1993; Welsh and Bowleg, 2022). Small islands generally depend on a combination of groundwater, surface water (when available), seawater

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desalination, and limited rainwater harvesting (Holding and Allen, 2016).

To carry out such prioritization effectively, a thorough understanding of watershed morphology is required. Within this context, watershed prioritization has emerged as a strategic approach. Although watershed management has been practiced for millennia, it gained renewed emphasis in the 1980s, mainly aimed at rehabilitating degraded lands, improving agricultural productivity, and diversifying rural livelihoods (Abdeta et al., 2020; López-Silva and Carmenates-Hernández, 2023). Prioritization involves classifying sub-watersheds to establish an order for implementing soil and water conservation measures, based on comprehensive assessments of the physical and environmental characteristics of each basin (Javed et al., 2011). This methodology is crucial for mitigating the impacts of climatic and anthropogenic pressures on watershed stability, thereby enhancing population resilience.

Watershed characterization typically relies on morphometric parameters, which are quantitative descriptors of topography and landform geometry (Singh, 2016; Villalta Echeverria et al., 2022; Krishnan and Arjun, 2024; Shekar and Mathew, 2023). These parameters include elevation, slope, drainage density, and basin shape, among others (Shekar et al., 2023). As topological and structural features, morphometric variables have a significant influence on a watershed's hydrological response (Sarkar et al., 2022). Their relative permanence over time allows for consistent assessment of watershed behavior and vulnerability (Abdeta et al., 2020). Numerous studies (Kanhaiya et al., 2019; Abdeta et al., 2020; Ismail et al., 2022; Boute et al., 2024; Mohammed et al., 2024; Yan et al., 2024) highlight the usefulness of geospatial analyses in watershed prioritization, enabling targeted resource allocation, improved restoration planning, and increased cost-efficiency in water management.

An illustrative example is Tenerife, Canary Islands (Spain), where arid conditions and increasing water demand have driven the development of innovative groundwater exploitation strategies (Ecker, 1976; De Miguel-García et al., 2023). Hydrogeological studies identified key recharge areas, informing the construction of galleries and deep wells to enable sustainable aquifer use. Complementary measures such as seawater desalination and wastewater reuse have further enhanced the island's water resilience.

Although various case studies illustrate effective water strategies in island environments, they often remain context-specific and lack generalizable methodologies. Despite the availability of various tools and approaches within the broader field of sustainable water and aquifer management, there remains a significant gap in methodologies specifically tailored for volcanic island systems. These insular environments present unique hydrogeological and ecological challenges, such as limited freshwater resources, porous volcanic soils, steep terrain, and intense anthropogenic pressures from expanding urban and agricultural activities. In particular, Santa Cruz Island in the Galápagos Archipelago faces increasing threats to its groundwater supply due to seawater intrusion, wastewater pollution, and growing demand, exacerbated by climate variability and land-use changes. Addressing these complex challenges requires a locally adapted, data-driven framework to prioritize watershed conservation and optimize water resource management for long-term sustainability. The Galápagos Islands, located ~1000 km off the Ecuadorian coast, comprise over 200 landforms, including islands, islets, and seamounts (Claudino-Sales, 2018). Renowned for their endemic biodiversity, the archipelago was declared a UNESCO World Heritage Site in 1978 (Savage et al., 2024). The high degree of endemism, including 42 % of vascular plants, 67 % of terrestrial vertebrates, and 20 % of marine species (Danulat and Edgar, 2002) has led to the adoption of strict zoning policies, as outlined in the 2017 Santa Cruz Island Zoning Plan (FCD, 2019), which delineates conservation, sustainable use, and transition zones. Galápagos, due to its volcanic origin, arid climate, porous soils, and fragile ecosystems, can be affected by multi-hazard events such as volcanic eruptions, flooding, and seismic activity (Mulas et al., 2025).

Among the Galápagos Islands, one territory presents particularly urgent management challenges. Within this broader context, Santa Cruz Island stands out as the archipelago's most populated and socioeconomically active territory. Its unique combination of ecological sensitivity, water scarcity, and increasing demand from both urban and agricultural sectors makes it an ideal case study for evaluating the applicability of morphometric watershed prioritization in insular volcanic settings. The island is home to approximately 17,333 inhabitants (INEC, 2022), concentrated in urban centers such as Puerto Ayora, Bellavista, and Santa Rosa, along with scattered rural communities. The island's limited water availability, owing to its volcanic geology and absence of permanent surface water bodies, has heightened dependence on basal aquifers recharged mainly during the short-wet season (January to April). Zoning plays a pivotal role in protecting these recharge areas, many of which fall within conservation zones with restricted human activity. Although limited and adapted to the island's arid conditions, agricultural activities on Santa Cruz (including small-scale farming and livestock raising) increase water demand and, if poorly managed, may contribute to nutrient runoff and soil erosion. These pressures, combined with urban expansion (particularly around Bellavista and Santa Rosa), pose risks of contamination and overexploitation of aquifers. Since the 1980s, elevated concentrations of Escherichia coli have been documented in Puerto Ayora's water supply (INGALA et al., 1989; Proctor & Redfern Int, 2003; López and Rueda, 2010), underscoring ongoing pressures on the island's hydrogeological systems. Although desalination plants have been introduced, their effectiveness remains limited. In this setting, watershed prioritization studies offer a valuable tool for identifying key recharge areas, evaluating vulnerability to natural and anthropogenic threats (including those posed by agriculture) and guiding protection strategies to secure sustainable access to drinking water.

The increasing global pressure on freshwater systems highlights the urgent need for localized, data-driven frameworks that can inform sustainable groundwater management, particularly in island environments. While numerous tools exist under the Sustainable Aquifer Management framework (Glendenning et al., 2012; Bolinches et al., 2022; Samani, 2020), their application to volcanic islands remains limited and often lacks integration with geomorphological indicators.

As Ramakrishnan et al. (2024) points out, insular systems require customized approaches that consider unique challenges such as steep terrain, porous geology, and concentrated land-use pressure. In this context, the present study addresses the following research question: Which watersheds on Santa Cruz Island possess the most favorable morphometric characteristics for sustainable water use and conservation, particularly in the face of growing agricultural demand? To answer this, a comprehensive morphometric analysis of 24 watersheds is conducted, evaluating key parameters such as shape, slope, drainage patterns, and relief. The aim is to develop a prioritization framework that: (1) identifies conservation-priority zones, (2) supports emergency resource allocation, and (3) contributes to the long-term resilience of the island's water supply system, including rural and agricultural areas.

By filling this methodological gap, the study offers a replicable model for watershed prioritization in volcanic island contexts, linking physical geography with strategic environmental planning. The novelty of this study lies in its application of morphometric watershed prioritization to a volcanic island system under strong ecological and sociohydrological constraints (an approach not previously applied in the Galápagos or similar island environments).

2. Material and methods

2.1. Overview of the study area

Santa Cruz Island (Fig. 1) is a shield volcano with an elliptical shape, rising to 864 m above sea level (Herrera et al., 2022), and covering a territorial area of 986 km^2, 97 % of this territory is proteccted by the

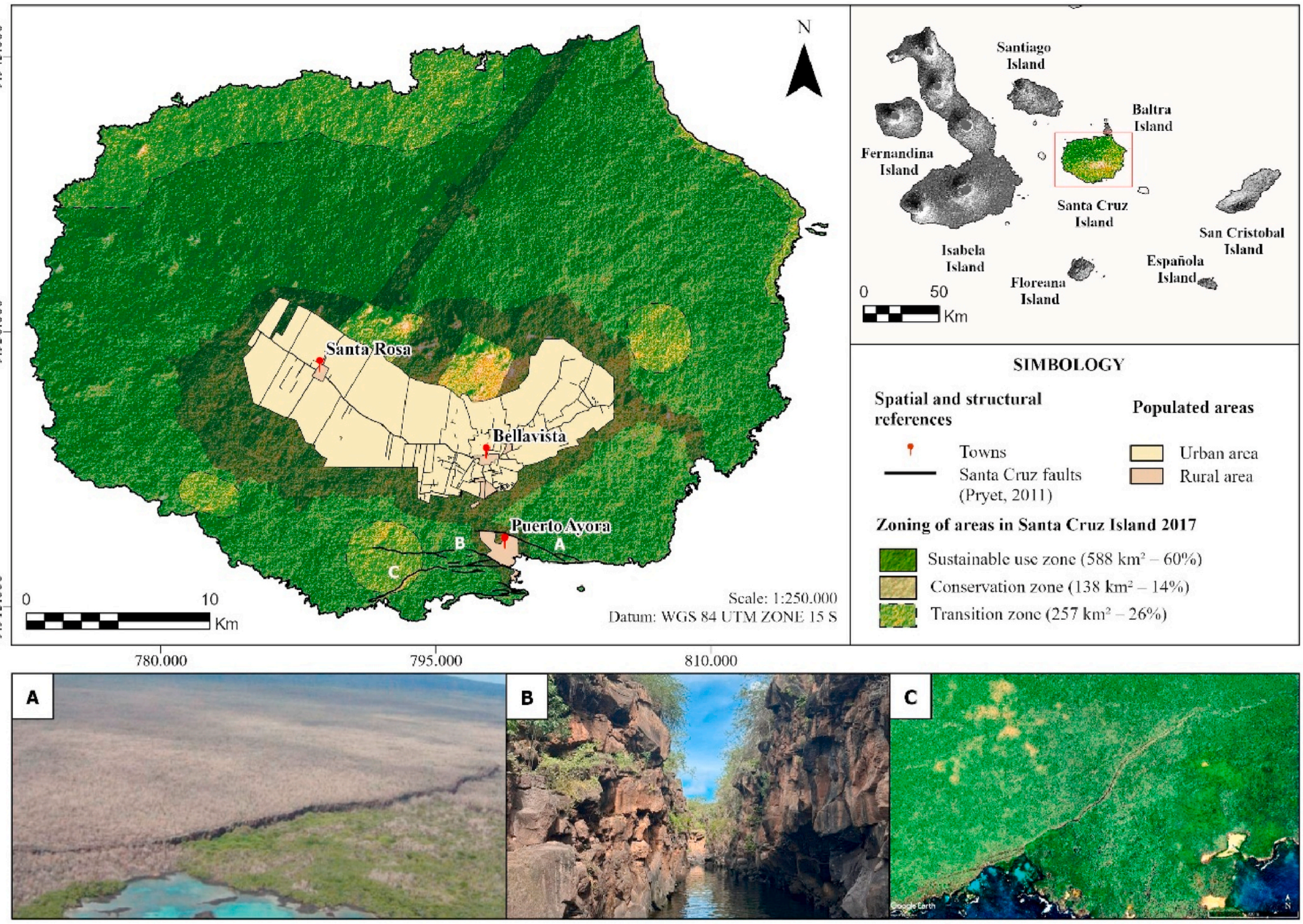

Fig. 1. Geographic location map of Santa Cruz Island, showing the zoning of sustainable areas, conservation areas, and transition zones. A) Puerto Ayora Fault (PAF). B) Tortuga Bay Fault (TBF) and Santa Cruz Church Fault (SCCF).C) Well Fault.

Galápagos National Park (Auken et al., 2009). Its summit features scoria cones and collapse craters aligned along an east-west oriented axial fissure system (McBirney and Williams, 1969; Schwartz, 2014). The island is traversed by faults trending east-west, visible along the north-east, east, and south coasts (Schwartz et al., 2022). According to Pryet (2011), these fault segments range in length from 2 to 6 km, with a principal component extending to depths of up to 10 m, and are spaced between 1 and 3 km apart.

The faults located on the northern flank of Santa Cruz Island exhibit an average orientation of 079° (WSW–ENE) and are characterized by pronounced scarps, accompanied by substantial debris accumulations at their bases (Schwartz, 2014). These faults are distributed across both the northern and southern sectors, forming narrow grabens that extend along the island's coastline. On the southern flank, the faults display a predominant orientation of 088° (W–E), affecting narrow monoclinal folds. The longest fault segment identified in the southern sector reaches a length of 5 km (Schwartz, 2014). The principal faults identified on Santa Cruz Island (Fig. 1) include the Puerto Ayora Fault (PAF), which has an average orientation of 108° and a minimum length of 5.8 km, forming the northern structure of the graben that bounds Puerto Ayora. The Tortuga Bay Trail Fault (TBTF), located to the south of Puerto Ayora, has an orientation of 115° and a minimum length of 3.2 km, defining the southern sector of the graben in which Puerto Ayora is located. Additionally, the UTM fault, with an orientation of 104°, is situated within the graben bounded by the Puerto Ayora and Tortuga Bay faults (Schwartz, 2014). Some structural features, although unnamed, are clearly visible in the hillshade map generated from the digital elevation model (Schwartz et al., 2022), such as the provisionally named Well Fault (Fig. 1).

The volcanic stratigraphy of Santa Cruz is divided into two principal series: the "Platform Series" (~1.6–1.1 Ma), primarily found in the north-eastern part of the island, and the "Shield Series" (~0.7 Ma), which is distributed across the island (Wilson et al., 2022). The Platform Series is mainly composed of basaltic lavas containing phenocrysts of plagioclase and olivine, whereas the Shield Series consists of transitional alkaline basalt lavas and aphyric lavas (Schwartz et al., 2022) characterized by the presence of large volcanic caves (Rodríguez et al., 2023). The lavas of both series do not exhibit dominant trends, and there is no clear internal consistency within the lavas of each series, suggesting that the magmas from which these lavas originated may have undergone complex and varied processes during their formation, including differing degrees of partial melting and varying depths within the Earth's mantle (Wilson et al., 2022).

The analysis of lavas from Santa Cruz (Wilson et al., 2022) highlights two significant trends related to the eruptive phases. One of these trends exhibits a marked influence of clinopyroxene fractionation, possibly linked to high-pressure and high-temperature conditions during a specific eruptive phase. In contrast, the other trend shows reduced clinopyroxene fractionation, suggesting less extreme conditions in terms of temperature, pressure, or magma composition during a separate eruptive episode (Wilson et al., 2022; Schwartz et al., 2022).

2.2. Data set collection

At present, there is a growing interest in the quantitative characterization of the Earth's topography, with the aim of modeling the interaction between various dynamic Earth systems, including atmospheric, geological, geomorphological, hydrological, and ecological processes (Wilson, 2018). However, these products are not exempt from errors inherent in data acquisition and processing. It is essential to correct issues that may compromise the accuracy of values recorded by remote sensing systems, taking into account factors such as spatial resolution, registration errors, missing or invalid pixels, vertical discrepancies, and horizontal shifts between datasets from different sources (Fisher and Tate, 2006; Yue et al., 2015). In this study, a Digital Elevation Model (DEM) from Landviewer platform with a spatial resolution of 4.7 m was used, generated from mosaics images downloaded from website (https://eos.com/landviewer). To reduce the aforementioned limitations, a topographic correction was applied using data provided by the Charles Darwin Foundation (the main research entity in the Galápagos Islands), based on contour lines derived from the SRTM 1 Arc-Second Global model, with a spatial resolution of 30 m. Through this official DEM provided by the CDF, the residual difference between both DEMs was calculated (with a mean error of +5.8 m), and this residual was subsequently added to the 4.7 m resolution DEM to enhance vertical accuracy and ensure greater consistency with official topographic references. Vertical discrepancies were assessed and found to have minimal impact on the morphometric analysis. This approach was considered appropriate, as the geospatial analysis of watersheds and drainage networks does not show significant variations when using either finer or coarser spatial resolutions, given that these are inherent characteristics of the terrain that remain largely unchanged.

2.3. Sub-watershed delineation and stream network generation

To delineate the watershed using the DEM, the hydrology toolboxes from ArcGIS Pro (version 3.4.1) were applied. The process begun with the "Flow direction" tool, which defines the water flow direction for each DEM's cell. Next, the "Flow accumulation" tool was applied to identify areas where surface runoff accumulates. Based on this information, an outlet point was selected within the river system, and the "watershed" tool was used to delineate the boundaries, determining the area that drains towards the selected outlet.

In watershed delineation, the calculated area was a horizontal projection of the watershed. This metric is crucial for watershed characterization, and has a direct influence in the water volume that can be accumulated. Watersheds are classified by their area according with the scheme proposed by Chelladurai et al. (2023). A "Region" encompasses more than 300 million hectares, while a "Basin" ranges from 30 to 300 million hectares. "Catchments" range from 10 to 30 million hectares, and "Sub-catchments" extend from 2 to 10 million hectares. "Watersheds" cover between 50,000 and 2 million hectares, followed by "Macro-watersheds", which occupy around 50,000 ha "Sub-watersheds" cover between 10,000 and 50,000 ha "Milli-watersheds" range from 1000 to 10,000 ha, "Micro-watersheds" range from 100 to 1000 ha, and finally, "Mini-watersheds" are the smallest units, ranging from 1 to 100 ha (Chelladurai et al., 2023). Finally, the drainage networks (flow lines), defined by Wohl (2009) as interconnected flow channels that converge towards a reference point, were determined through the vectorization of the connected flow grids.

In Santa Cruz Island, a total of 21,857 watershed-related features were identified. From the total, 20,609 (94.3 %) features were classified as "unclassified" because they did not meet the size criterion proposed by Chelladurai et al. (2023), whose methodology excludes polygons smaller than 100 ha, considering them non-representative. After filtering the records, a set of 1248 classifiable units was obtained, distributed into three categories: 24 (1.9 %) features correspond to "Sub-watersheds", 61 (4.9 %) to "Micro-watersheds", and 1163 (93.2 %) to "Mini-watersheds". For the morphometric analysis, the 24 sub-watersheds were selected due to their larger scale and spatial relevance in relation to the island's rural and urban areas. These were delineated in vector format using the "Catchment polygon processing" tool. Fig. 2 shows the spatial distribution of the sub-watersheds and their respective drainage networks, while Fig. 3 presents a flowchart illustrating the overall methodology used.

Fig. 3 outlines the methodology for watershed characterization and prioritization to support water resource management. The process involves generating a DEM, delineating sub-watersheds and drainage networks using GIS tools, calculating key morphometric parameters, and integrating them into a composite index to rank sub-watersheds based on their physical attributes.

2.4. Quantification of morphometric parameters

To carry out this analysis, 18 morphometric parameters were carefully selected based on their established relevance in hydrological and geomorphological studies. These parameters maintain direct or inverse relationships with processes such as surface runoff, peak discharge, and soil erosion risk (Ratnam et al., 2005; Javed et al., 2009; Singh and Singh, 2014). Their selection was guided by three main criteria: (i) hydrological significance, (ii) representation across major morphometric domains (shape, linear, relief characteristics), and (iii) suitability for GIS-based extraction from DEMs.

The chosen set avoids redundancy by excluding highly correlated or derivative indices that would not significantly improve the prioritization outcome but could introduce multicollinearity. This approach aligns with prior studies (Abdeta et al., 2020) and ensures a robust, yet operationally efficient prioritization framework, particularly relevant in data-scarce volcanic island environments like the Galápagos.

Morphometric characterization was performed after delineating the sub-catchments and extracting their respective drainage networks. At this stage, primary morphometric parameters (such as area, perimeter, catchment length, maximum and minimum elevation, mainstream length, and number of streams) were derived using the spatial analysis tools of ArcGIS Pro (Table 1).

Based on these basic parameters, other morphometric indicators were derived using standardized mathematical formulas (Table 1), widely employed in hydrological studies, and using the previously calculated data as a foundation (Table S1; Supplementary material). To structure the analysis, the parameters were classified into four categories: shape, linear, area, and relief. Furthermore, complementary methodologies and approaches proposed in the scientific literature were reviewed to enrich the analytical framework.

To provide a general overview, basic statistical values (mean, minimum, maximum, and standard deviation) were calculated for all derived morphometric parameters (Table 2). This summary supports the identification of variability among the 24 sub-watersheds, and serves as a basis for the detailed interpretation presented in the *Results* section.

2.5. Sub-watershed prioritization using a rank-based compound method

The linear and relief morphometric parameters show a direct correlation with soil susceptibility to erosive processes (Ratnam et al., 2005; Sujatha et al., 2013; Singh and Singh, 2014). In this context, high values of these parameters are associated with greater soil erodibility within the watershed. Consequently, sub-watersheds exhibiting the highest values are assigned the highest priority (rank 1), followed in descending order, with the sub-watershed presenting the lowest value receiving the lowest rank. In contrast, parameters related to area and shape display an inverse relationship with soil erodibility (Javed et al., 2009; Raja et al., 2017); in this case, lower values indicate greater vulnerability to erosion. According to this criterion, sub-watersheds with the lowest values for these parameters are assigned the highest priority ranks, whereas those with higher values receive lower ranks.

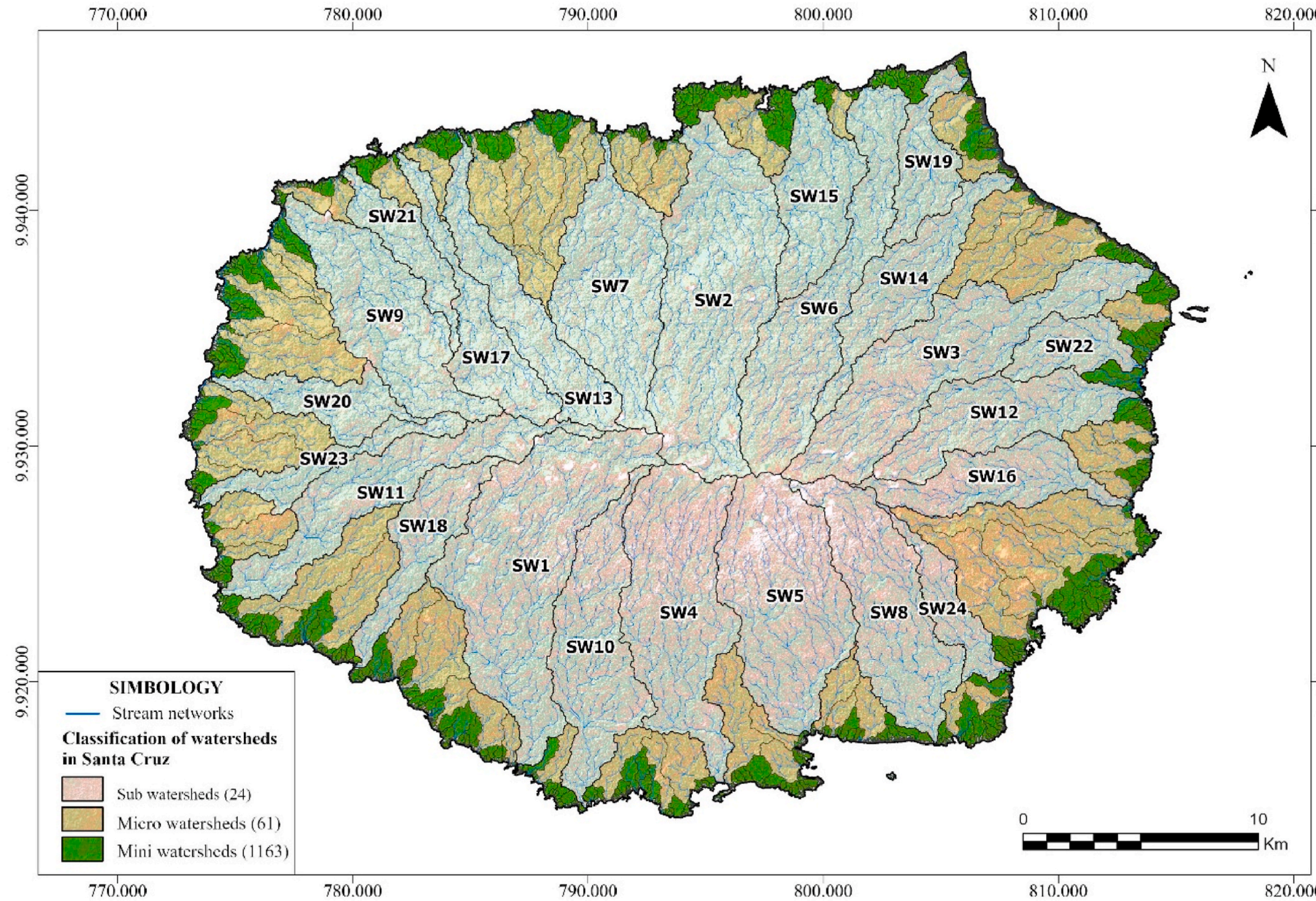

Fig. 2. Distribution of sub-watersheds on Santa Cruz Island: 24 sub-watersheds, 61 micro-watersheds, and 1163 mini-watersheds.

Sub-watershed prioritization was carried out using the compound method of rank average, which assumes that all morphometric parameters have equal weighting in the final classification (Farhan, 2017). For its application, each sub-watershed was assigned a rank based on the value obtained for each of the eighteen selected parameters. Composite values were then calculated by summing the ranks for each sub-watershed and dividing by the total number of parameters. The sub-watershed with the lowest composite value was considered the highest priority (rank 1), while the one with the highest value was ranked last. This approach enables the identification of sub-watersheds with higher potential for surface runoff, peak discharge, and erosion processes, which serves as a key input for the implementation of differentiated strategies for the management and conservation of water and soil resources, tailored to the sensitivity level of each hydrological unit.

3. Results

This section presents the results obtained for each group of morphometric parameters: shape, linear, areal, and relief. The calculated values for the analyzed watersheds are described, and a brief interpretation is provided regarding the potential implications of each parameter in terms of hydrological behavior and the physical characteristics of the watersheds.

3.1. Shape morphometric parameters

These parameters describe the general shape of the basin, including its degree of elongation, compactness, and circularity. They are useful for inferring the hydrological response and surface runoff dynamics.

Watershed area (A) determines its capacity to capture and store water, directly influencing the volume it can retain or drain. In Santa Cruz, catchment sizes range from a maximum of 60.70 km^2 (SW1) to a minimum of 10.07 km^2 (SW24). Smaller watersheds tend to respond more rapidly to rainfall events, which can intensify erosion and increase water turbidity at discharge points.

Perimeter (P) is the total length of the catchment boundary and directly influences runoff potential (Rao, 2020). In Santa Cruz, the perimeter ranges from a maximum of 54.42 km (SW3) to a minimum of 20.69 km (SW22), reflecting variability in watershed shape and flow paths.

Maximum elevation (H) indicates the topographic gradient and energy potential of the catchment. The highest elevation is 860 m a.s.l. (SW5), while the lowest is 125 m a.s.l. (SW22), suggesting notable differences in slope and runoff energy. In contrast, Minimum elevation *(h)*, commonly located at outlet points, influences the base level for surface runoff. It ranges from 13 m a.s.l. (SW19) to 0 m a.s.l., the latter being common among several catchments (e.g., SW1, SW2, SW3, SW6), indicating a direct connection to coastal zones and potential marine influence.

Watershed length (L_b) represents the longest dimension of the catchment, aligned with the main stream channel, and is closely related to runoff concentration time and surface drainage efficiency (Schumm, 1956). In Santa Cruz, watershed length ranges from a maximum of 13.46 km (SW1) to a minimum of 4.87 km (SW24), indicating variability in hydrological response times.

Stream order (U) measures the hierarchical branching level of tributaries within a catchment and is key to understanding the structural

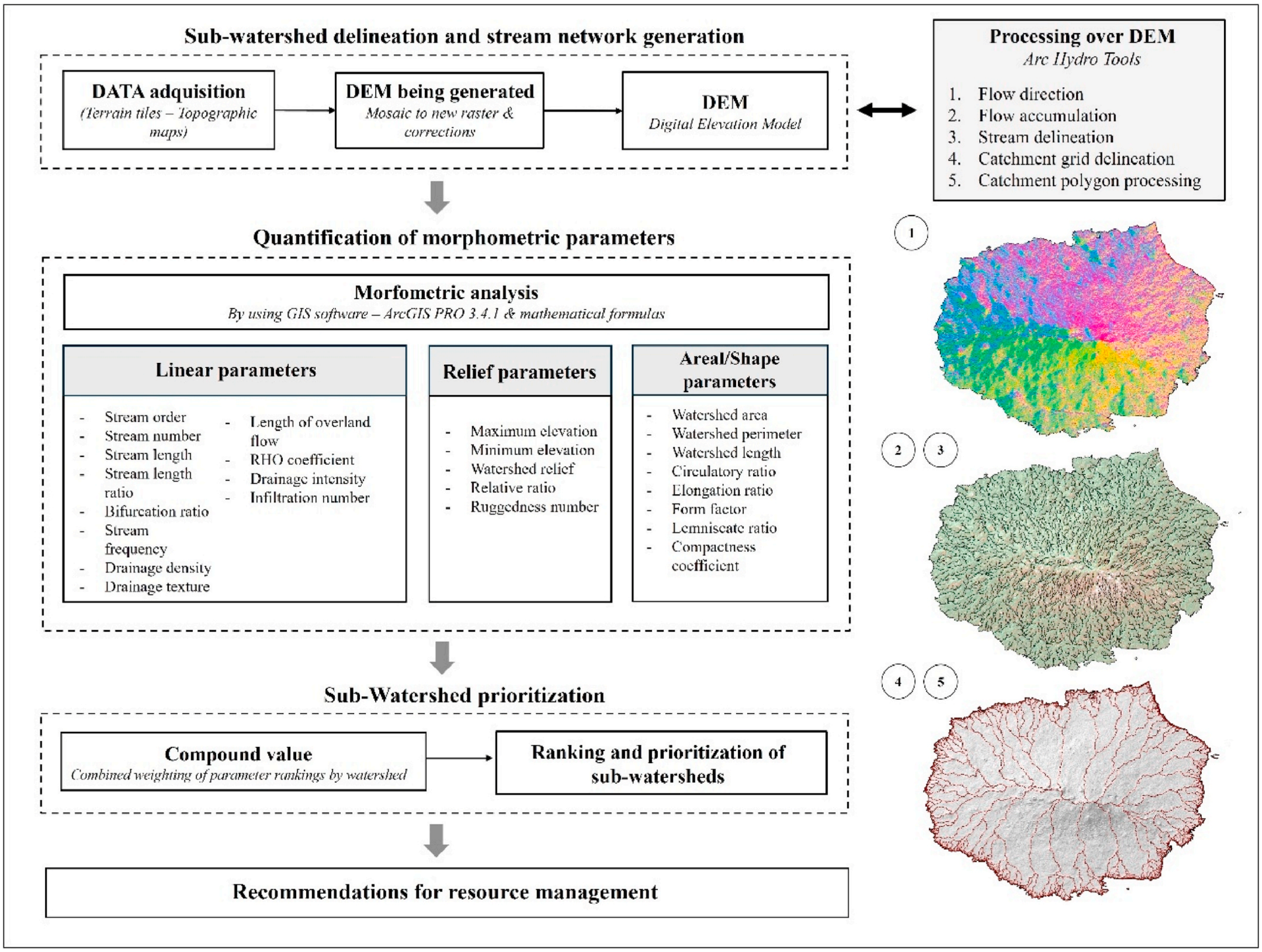

Fig. 3. Methodological diagram for watershed prioritization on Santa Cruz Island, Galápagos.

complexity of the drainage system. The highest stream order observed is 6th (SW1), suggesting a more developed drainage network, while all other catchments range from 4th to 5th order, with the 4th order being the lowest observed, associated with simpler hydrological structures.

Number of stream (N_u) refers to the total count of stream segments within a catchment, serving as an indicator of the complexity and degree of development of the drainage network. In Santa Cruz, Nu values range from a maximum of 1692 in SW2 to a minimum of 271 in SW23, with a mean of 770 across all sub-watersheds. The higher number of channels in SW2 reflects a more intricately branched system, often linked to steeper slopes, finer soils, and higher runoff potential. In contrast, the limited network in SW23 suggests simpler topography and potentially greater infiltration capacity. First-order streams dominate the network, with a total of 10,270 segments, and the only sixth-order stream appears in SW1, indicating it has the most hierarchically developed system (Table 3).

Stream length (L_u) represents the total length of all flow paths within each catchment's drainage system, reflecting its spatial extent and hydrological capacity. The longest cumulative stream length is recorded in SW1 (1.47 km), suggesting a more extensive and developed fluvial system. Conversely, SW18, with only 0.68 km, exhibits a lower degree of drainage network development. On average, total stream length per basin is 0.89 km, with individual stream orders showing relatively consistent contributions: first-to fifth-order channels range between 0.18 and 0.26 km, while the sixth-order stream (present only in SW1) adds 0.22 km, reinforcing its significance in the hydrological structure of the island (Table 3).

3.2. Linear morphometric parameters

Linear morphometric parameters include measurements such as stream length, stream order, and drainage density. They allow for the characterization of the drainage network and its influence on hydrological connectivity.

Bifurcation ratio (R_b) is the ratio between the total number of streams of a specific order (Nu) and the number of streams of the next higher order (N_u+1) (Schumm, 1956). This index is linked to the branching pattern of the drainage network, reflecting the degree of connectivity between streams of different orders (Horton, 1945). In Santa Cruz, R_b values ranged from a maximum of 31.34 (SW18) to a minimum of 5.95 (SW9). High values may indicate structural control or anomalies in the drainage system, while lower values suggest less disturbed and more natural drainage patterns (Suji et al., 2015), (Table S2; Supplementary material).

Stream length ratio (R_l) is defined as the ratio between the mean length of streams of a given order (L_u) and the mean length of streams of the next lower order ($L_u - 1$) (Horton, 1945). Generally, the mean length of streams of a given order is greater than that of the lower-order streams. This ratio provides information about the chronological development of stream segments and the relative permeability of rock

Table 1
Summary of formulas and methodological approaches applied for the quantitative characterization of watershed morphometric parameters (Abdeta et al., 2020).

Parameters and aspects	Formulas/methods	Units	References
Shape aspects			
Area (*A*)	GIS software analysis	km^2	
Perimeter (*P*)	GIS software analysis	km	
Maximum elevation (*H*)	GIS software analysis	m a.s.l.	
Minimum elevation (*h*)	GIS software analysis	m a.s.l.	
Length (L_b)	$L_b = 1.312 \text{ x } A^{0.568}$	km	Nookaratnam et al. (2005)
Stream order (*U*)	Hierarchical rank	Dimensionless	Strahler (1964)
Stream number (N_u)	$N_u = N_{u1} + N_{u2} + \cdots + N_{un}$	Dimensionless	Horton (1945)
Stream length (L_u)	$L_u = L_{u1} + L_{u2} + \cdots + L_{un}$	km	Horton (1945)
Linear aspects			
Mean stream length (L_{sm})	Average of stream length of all orders	km	Horton (1945)
Bifurcation ratio (R_b)	$R_b = N_u/N_{u+1}$	Dimensionless	Schumm (1956)
Stream length ratio (R_l)	$R_l = L_u/L_{u-1}$	Dimensionless	Horton (1945)
Mean bifurcation ratio (R_{bm})	Average of bifurcation ratios of all orders	Dimensionless	Schumm (1956)
Mean stream length ratio (R_{lm})	Average of stream length ratios of all orders	Dimensionless	Schumm (1956)
Stream frequency (F_s)	$F_s = N_u/A$	km^{-2}	Schumm (1956)
Drainage density (D_d)	$D_d = L_u/A$	km/km^2	Schumm (1956)
Drainage texture (D_t)	$D_t = N_u/P$	km^{-1}	Schumm (1956)
Length of overland flow (L_o)	$L_o = 1/(2D_d)$	km	Schumm (1956)
Drainage intensity (D_i)	$D_i = F_s/D_d$	km^{-1}	Faniran (1968)
RHO coefficient (ρ)	R_{lm}/R_b		Horton (1945)
Inftration number (I_f)	$I_f = F_s \times D_d$	km^{-3}	Faniran (1968)
Relief aspects			
Relief (B_h)	$B_h = H\text{–}h$	km	Strahler (1964)
Relief ratio (R_h)	$R_h=B_h/L_b$	Dimensionless	Schumm (1956)
Relative relief (R_{hp})	$R_{hp} = H \times 100/P$	Dimensionless	Melton (1957)
Ruggedness number (R_n)	$R_n=B_h \times D_d$	Dimensionless	Strahler (1964)
Area aspects			
Circulatory ratio (R_c)	$R_c = 4\pi A/P^2$; $\pi = 3.14$	Dimensionless	Miller (1953)
Elongation ratio (R_e)	$R_e=(2/Lb) \times (A/\pi)^{0.5}$	Dimensionless	Schumm (1956)
Form factor (F_f)	$F_f = A/ L_b^2$	Dimensionless	Horton (1945)
Lemniscates ratio (*K*)	$K = L_b^2/ 4A$	Dimensionless	Chorley et al. (1957)
Compactness coefficient (C_c)	$C_c = P/2\ (\pi A)^{0.5}$	Dimensionless	Horton (1945)

formations within a watershed (Table S2; Supplementary material). Horton (1945) formulated two fundamental laws that describe the structural behavior of drainage networks in a watershed, related to the number and length of streams.

- *Law of stream numbers*: This law states that the number of stream channels decreases in an inverse geometric manner as stream order increases, with the bifurcation ratio forming the base of this progression. In the analyzed sub-watersheds, this relationship consistently holds true (Fig. 4; Fig. 6), as evidenced by a strong inverse correlation between stream order and stream quantity, with coefficients of determination (R^2) ranging from 0.80 (in SW8) to 1.00 (in SW17).

Table 2
Summary statistics of morphometric parameters across 24 sub-watersheds.

Parameters	Mean	Min	Max	Std. Dev.
Area (*A*)	28.19	10.07	60.27	15.13
Perimeter (*P*)	38.39	20.69	54.42	9.14
Maximum elevation (*H*)	552.50	125.00	860.00	223.36
Minimum elevation (*h*)	1.04	0.00	13.00	2.61
Length (L_b)	8.44	4.87	13.46	2.64
Highest stream order (U)	4.29	4.00	6.00	0.55
Stream number (N_u)	769.75	271.00	1692.00	407.12
Stream length (L_u)	0.89	0.68	1.47	0.16
Mean stream length (L_{sm})	0.21	0.19	0.24	0.01
Bifurcation ratio (R_b)	10.62	5.95	31.34	6.08
Stream length ratio (R_l)	3.27	2.30	4.97	0.59
Mean bifurcation ratio (R_{bm})	3.20	1.98	10.45	1.79
Mean stream length ratio (R_{lm})	0.99	0.77	1.13	0.09
Stream frequency (F_s)	27.36	23.66	29.20	1.24
Drainage density (D_d)	0.04	0.01	0.08	0.02
Drainage texture (D_t)	19.25	7.74	36.21	7.72
Length of overland flow (L_o)	15.55	5.94	35.63	7.39
Drainage intensity (D_i)	854.49	321.82	2030.67	419.20
RHO coefficient (ρ)	0.11	0.02	0.18	0.04
Inftration number (I_f)	1.12	0.40	2.41	0.59
Relief (B_h)	551.46	125.00	859.00	224.22
Relief ratio (R_h)	64.28	24.97	85.75	16.64
Relative relief (R_{hp})	1399.35	604.23	2483.18	426.42
Ruggedness number (R_n)	19.02	9.10	34.45	6.68
Circulatory ratio (R_c)	0.23	0.11	0.47	0.08
Elongation ratio (R_e)	52.90	17.45	117.95	30.19
Form factor (F_f)	0.38	0.33	0.42	0.03
Lemniscates ratio (*K*)	0.67	0.59	0.75	0.05
Compactness coefficient (C_c)	2.16	1.46	3.05	0.37

Table 3
Summary of number and total length of streams by order (1st to 6th) for the 24 sub-watersheds of Santa Cruz Island.

To.no.	Stream Orders	Code of Watersheds			
		Total	Max	Min	Mean
1	Number of stream (N_u)	18,474	1692	271	770
	1st Order (N_{u1})	10,270	947	150	428
	2ndOrder (N_{u2})	4926	471	59	205
	3rd Order (N_{u3})	2409	219	31	100
	4th Order (N_{u4})	771	140	3	32
	5th Order (N_{u5})	69	31	1	12
	6th Order (N_{u6})	29	29	29	29
2	Length of stream (L_u)	21.41	1.47	0.68	0.89
	1st Order (L_{u1})	4.89	0.23	0.18	0.20
	2ndOrder (L_{u2})	5.30	0.26	0.19	0.22
	3rd Order (L_{u3})	5.14	0.26	0.18	0.21
	4th Order (L_{u4})	4.77	0.26	0.08	0.20
	5th Order (L_{u5})	1.10	0.26	0.04	0.18
	6th Order (L_{u6})	0.22	0.22	0.22	0.22

- *Law of stream lengths:* According to this law, the average length of streams increases progressively with order, following a direct geometric series. However, in the analysis conducted, this relationship appeared weak or inconsistent in several sub-watersheds (Fig. 5; Fig. 6), with R^2 values ranging from 0.0003 (in SW8) to 0.84 (in SW17). This variability suggests the influence of local factors such as lithology, geological structures, and active geomorphological processes, including water erosion, which may be affecting the natural longitudinal development of the channels.

The scatter plot in Fig. 6 compares the coefficients of determination (R^2) obtained from Horton's first law (logarithmic relationship between

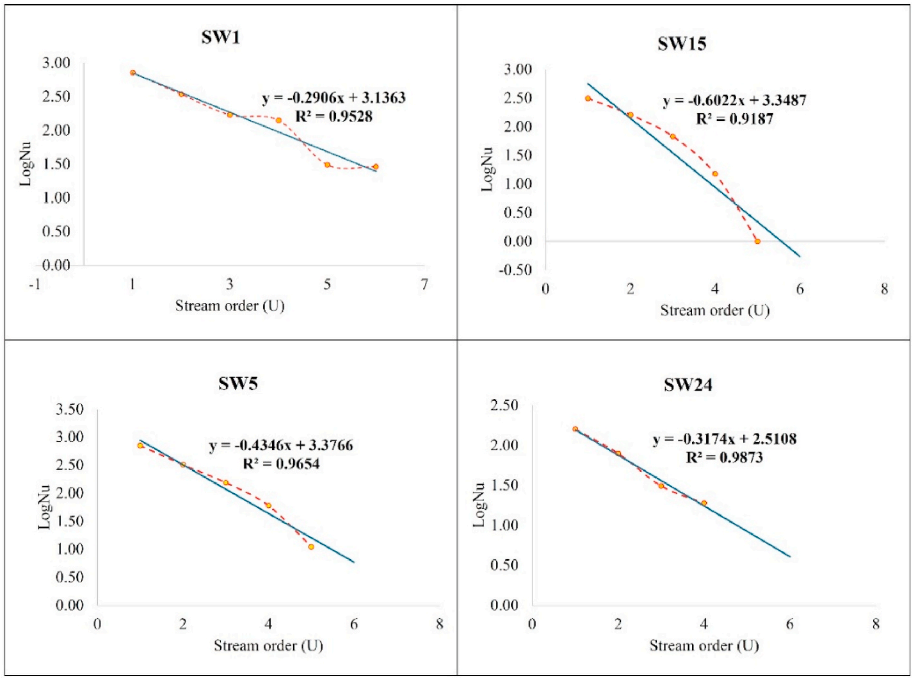

Fig. 4. Relationship between stream number (Log N_u) and stream order for sub-watersheds SW1, SW15, and SW24.

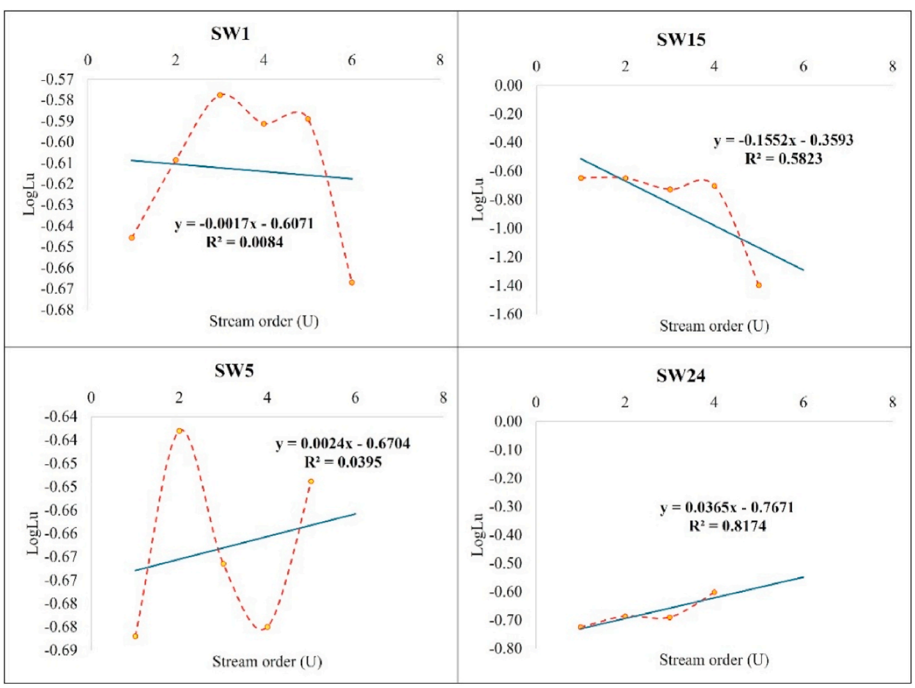

Fig. 5. Relationship between length of stream (Log L_u) and stream order for sub-watersheds SW1, SW15, and SW24.

stream number and stream order, plotted on the x-axis) and Horton's second law (logarithmic relationship between stream length and stream order, plotted on the y-axis) across the 24 sub-watersheds. Two threshold lines at $R^2 = 0.6$ and $R^2 = 0.95$ are included to help interpret the degree of fit for each law. The distribution of points illustrates the variability in how consistently each sub-watershed conforms to Horton's theoretical models. Points located near the upper-right quadrant reflect a strong agreement with both laws, while those dispersed in the lower-left quadrant indicate a weaker or inconsistent correlation, suggesting local geomorphic or structural controls affecting drainage development.

Stream frequency (F_s) indicates the total number of channels per unit area and is directly related to drainage density (Horton, 1945; Prabhakaran and Raj, 2018). It provides insight into the degree of fluvial network development. In Santa Cruz, Fs ranges from a maximum of 29.20 (SW12) to a minimum of 23.66 (SW1). Higher frequencies indicate a more dissected terrain with a denser network of flow paths, while lower values suggest broader spacing between channels and less drainage intensity.

Drainage density (D_d) refers to the total length of stream channels per unit area. It measures the cumulative length of streams relative to the

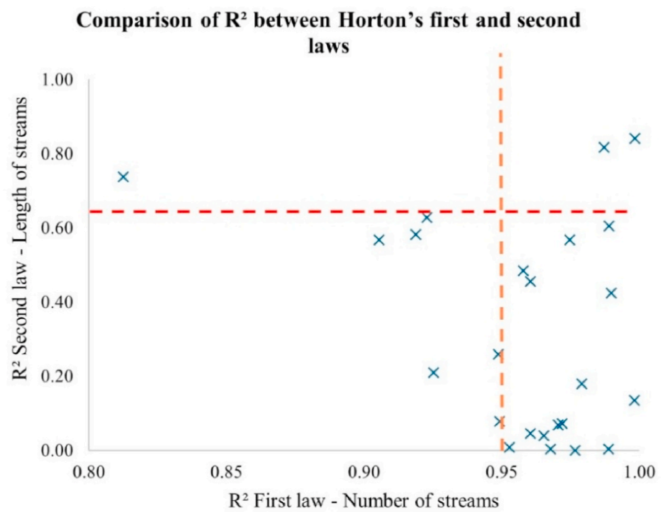

Fig. 6. Scatter plot comparing the coefficient of determination (R^2) for Horton's first law (x-axis) and second law (y-axis) across the 24 sub-watersheds of Santa Cruz Island. The thresholds $R^2 = 0.6$ and $R^2 = 0.95$ serve as reference lines to evaluate the strength of the logarithmic fit for each law. Each point represents a sub-watershed, highlighting the variability in morphometric behavior and the degree of alignment with Horton's drainage theory.

basin area (Horton, 1945). It ranges from a maximum of 0.084 km/km^2 (SW24) to a minimum of 0.014 km/km^2 (SW2). High values are typically associated with steeper slopes, lower infiltration, and higher runoff generation, while low values may indicate gentle topography, higher infiltration capacity, or less developed channel systems.

Drainage texture (D_t) represents the number of stream channels relative to the perimeter of a watershed (Horton, 1945). This index helps assess how spaced or concentrated the drainage lines are within the basin boundary. The lowest values are found in SW2, SW5, and SW7, while the highest are in SW23 and SW24.

Length of overland flow (L_0) is a parameter that reflects the distance water travels over the land surface before entering the stream channel and is inversely related to the drainage density (D_d). According to Horton's (1945) proposal, it is estimated as half the inverse of the drainage density. Values range from a maximum of 35.63 m (SW2) to a minimum of 5.94 m (SW24), indicating notable variation in surface flow distances. Higher Lo values reflect longer runoff paths before channelization, often associated with lower drainage densities and gentler slopes.

Drainage intensity (D_i) is defined as the ratio between stream frequency (F_s) and drainage density (Dd), according to Faniran (1968), and represents the efficiency of the drainage system in a watershed. The highest D_i is observed in SW2 (2030.67), suggesting high runoff efficiency, while the lowest is in SW24 (339.47), indicating a less efficient drainage system.

RHO coefficient (ρ) coefficient represents the proportion between drainage density and stream frequency and helps evaluate the interaction between the drainage system geometry and the watershed's physiography. Values range from a minimum of 0.024 (SW18) to a maximum of 0.178 (SW24), where higher values suggest greater morphological complexity in the drainage network.

The *infiltration number (I_f)*, also proposed by Faniran (1968), is calculated as the product of drainage density and stream frequency. The lowest If is 0.58 (SW1), suggesting high infiltration capacity, while the highest is 2.41 (SW24), indicating low infiltration and high surface runoff potential. Sub-basins from SW1 to SW8 generally show favorable infiltration conditions, while SW20–SW24 represent areas with the least infiltration potential.

3.3. Relief morphometric parameters

Relief morphometric parameters analyze the basin's topography through indicators such as mean slope, maximum elevation, and elevation range. They are key to understanding the relief energy and erosion potential.

Relief ratio (R_h) is the ratio between the maximum relief of the watershed and the maximum length of the watershed, which is parallel to the main drainage line. It measures the overall slope of a watershed and is an indicator of the processes and intensity of erosion on the watershed slopes (Schumm, 1956).

Relative relief (R_{hp}) is calculated using the perimeter and relief of the watershed (Melton, 1957). It provides a measure of the elevation variability within the watershed. A high value indicates a watershed with significant altitude variations, suggesting a more rugged or steep topography. In contrast, a low value indicates a watershed with a gentler, less varied relief. In Santa Cruz, R_{hp} values range from a maximum of 2483.18 (SW5), indicating highly rugged topography, to a minimum of 604.23 (SW22), suggesting smoother, less varied terrain.

Ruggedness number (R_n) is the product of total relief and drainage density, combining the slope of the terrain with its length. The highest R_n value is 34.45 (SW24), pointing to steep and dissected landscapes, while the lowest is 9.10 (SW19), reflecting gentler topographic conditions and lower surface energy.

3.4. Areal morphometric parameters

Areal morphometric parameters are related to the basin's spatial extent and distribution, including drainage area, elongation ratio, and drainage density. They help assess the catchment's capacity and its response to hydrometeorological events.

Circulatory ratio (R_c) compares the watershed area with that of a circle having the same perimeter (Miller, 1953; Abdeta et al., 2020), serving as an indicator of hydrological efficiency. Values range from a minimum of 0.11 (SW23) to a maximum of 0.47 (SW5). Lower Rc values suggest elongated catchments with longer concentration times and lower flash flood potential, while higher values indicate more circular basins with quicker runoff response.

Elongation ratio (R_e) represents the relationship between the diameter of a circle with the same area as the watershed and its maximum length, providing a measure of its relative shape (Schumm, 1956). Values close to 1 indicate more circular and symmetrical watersheds, while lower values suggest an elongated morphology. In Santa Cruz, the most elongated basins are SW1 (117.95) and SW2 (116.06), while the most compact are SW24 (17.45) and SW23 (18.22), reflecting differences in hydrological response potential.

Form factor (F_f) is a morphometric parameter that relates the area of the watershed to the square of its maximum length (L_b) (Godif and Manjunatha, 2022). Low values indicate elongated watersheds, while high values reflect more circular shapes, which tend to generate more intense peak discharges in shorter times (Horton, 1945). The lowest values, observed in SW1 and SW2 (0.33), indicate elongated shapes and lower risk of rapid runoff. The highest values, 0.42 in SW24 and SW23, suggest more compact forms with potentially faster peak discharges.

Lemniscates ratio (K) is used to determine the gradient of a watershed (Chorley et al., 1957). The highest values are 0.75 (SW1 and SW2), suggesting more elongated forms with gradual slopes, while the lowest values are 0.59 (SW24, SW23, SW22), indicating steeper and more compact shapes.

Compactness coefficient (C_c) is the ratio between the perimeter of the watershed and the circumference of the equivalent circular area of the watershed (Horton, 1945). It is independent of the size of the watershed but depends on the slope (Abdeta et al., 2020). In this analysis, the watersheds with the lowest values were SW5.

3.5. Ranking of watersheds

Using the natural breaks methodology of Jenks (1967) and based on the values obtained for the compound parameter (C_p), the sub-watersheds were classified into three priority levels. Those with values less than or equal to 11.72 were classified as high priority, while those with values less than or equal to 13.33 were assigned medium priority, and those with values lower than 15.33 were considered low priority.

The following tables present the parametric ranking results for each morphometric variable, the computed compound parameter, and the final priority level assigned to each sub-watershed (Table 4; Table 5). The ranking is based on the direct or inverse relationship of each parameter with sub-watershed vulnerability, following the methodology proposed by Abdeta et al. (2020). A total of 18 key morphometric parameters (covering linear, relief, and areal aspects) were considered the most representative for this analysis.

4. Discussion

The prioritization analysis based on morphometric parameters identified sub-watersheds with varying degrees of susceptibility to erosion. Using the compound parameter (C_P) method, which integrates both directly and inversely correlated indicators, the sub-watersheds were ranked and grouped into three categories: high, medium, and low priority (Fig. 7). The highest priority was assigned to SW7 (C_P = 9.83), SW5 (C_P = 9.94), and SW24 (C_P = 10.39), indicating a greater potential for erosion due to unfavorable morphometric characteristics. In contrast, SW1 (C_P = 14.33), SW19 (C_P = 14.61), SW22 (C_P = 15.00), and SW15 (C_P = 15.33) were categorized as low priority, reflecting lower susceptibility (Table 4; Table 5). This ranking provides a useful basis for targeted soil conservation and watershed management strategies.

High-priority sub-watersheds exhibit morphometric characteristics that indicate a higher risk of erosion and water loss, which could negatively impact both the availability and quality of water resources. Therefore, these areas require immediate intervention focused on soil conservation, runoff control, and infiltration techniques to mitigate erosion and improve water management. From an agricultural perspective, such interventions are crucial to preserve soil fertility, reduce sediment transport into croplands, and ensure the sustainability of irrigation practices, particularly in areas where local communities depend on small-scale farming. In contrast, low-priority sub-watersheds show lower susceptibility to erosion, making them more suitable for water resource conservation and potentially more compatible with sustainable agricultural development. Their higher retention capacity and soil stability offer favorable conditions for water harvesting and the planning of irrigation systems, especially for crops requiring regular water supply throughout dry seasons. To clarify why certain sub-watersheds are more suitable for agriculture, the prioritization was primarily based on morphometric parameters that reflect erosion susceptibility and water retention capacity. Low-priority sub-watersheds exhibit greater soil stability and higher water retention, which create favorable conditions for sustainable agriculture by preserving soil fertility and ensuring reliable irrigation during dry periods. Conversely, high-priority sub-watersheds are more prone to erosion and water loss, thus requiring immediate conservation measures before being considered suitable for agriculture.

It is important to note that while morphometric analysis provides valuable preliminary insights, complementary field studies, including water quality assessments, are necessary to fully confirm the agricultural suitability of these areas. However, to confirm this suitability, complementary studies (including field sampling and geochemical analyses) are essential to determine whether the available water meets the necessary quality standards for use. This classification thus not only guides intervention and conservation strategies but also significantly narrows the geographic scope for identifying potential water resources, optimizing technical and logistical efforts in the field.

The island of Mayotte, part of the Comoros archipelago, has faced a severe water crisis since 2022, marked by extreme scarcity and source contamination, which led to strict water rationing. In December 2024, the situation worsened with the passage of Cyclone Chido, prompting the French government to declare a state of natural disaster (France24, 2024; Colliva, 2023). However, the impacts were partially mitigated thanks to hydrological studies conducted in 2019, which included hydro-geomorphological analyses to assess watershed conditions and prioritize interventions.

Cases like Mayotte highlight the strategic value of hydrological studies and should be seen as both a warning and an opportunity for other volcanic islands, such as Santa Cruz in the Galápagos. Before the passage of Cyclone Chido in December 2024, Mayotte was already facing a critical humanitarian and environmental situation characterized by widespread poverty, inadequate access to clean water (only 71 % of households had running water), fragile health infrastructure

Table 4
Hierarchical ranking of each morphometric parameter, the compound parameter and priority ranking for sub-watersheds SW1 to SW12.

ID	Parameters	Computed parametric ranks											
		SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12
1	Mean bifurcation ratio (R_{bm})	20	12	3	11	6	9	8	16	24	13	4	17
2	Mean stream length ratio (R_{lm})	14	15	18	20	8	13	4	12	11	6	21	17
3	Stream frequency (F_s)	24	4	9	28	8	14	7	11	2	16	5	1
4	Drainage density (D_d)	17	24	23	21	16	22	19	18	20	14	15	13
5	Drainage texture (D_t)	4	2	8	5	1	10	3	6	7	11	13	9
6	Length of overland flow (L_o)	8	1	2	4	9	3	6	7	5	11	10	12
7	Drainage intensity (D_i)	12	1	2	8	6	3	5	7	4	10	9	11
8	RHO coefficient (ρ)	18	13	23	17	22	14	15	8	1	12	21	6
9	Infltration number (I_f)	23	24	21	20	17	22	16	18	19	15	14	13
10	Relief (B_h)	6	3	4	5	1	2	7	8	16	9	11	13
11	Relief ratio (R_h)	19	15	13	12	7	4	6	8	21	9	11	18
12	Relative relief (R_{hp})	9	4	12	5	1	6	2	3	18	8	17	14
13	Ruggedness number (R_n)	10	20	16	13	7	9	11	14	21	15	18	19
14	Circulatory ratio (R_c)	17	23	10	18	24	9	22	19	16	12	2	15
15	Elongation ratio (R_e)	24	23	22	21	20	19	18	17	16	15	14	13
16	Form factor (F_f)	1	2	3	4	5	6	7	8	9	10	11	12
17	Lemniscates ratio (K)	24	23	22	21	20	19	18	17	16	15	14	13
18	Compactness coefficient (C_c)	8	2	15	7	1	16	3	6	9	13	23	10
Compound parameter (Cp)		14.33	11.72	12.56	13.33	9.94	11.11	9.83	11.28	13.06	11.89	12.94	12.56
Ranking		1	2	3	4	5	6	7	8	9	10	11	12
Final priority		Low	High	Medium	Medium	High	High	High	High	Medium	Medium	Medium	Medium

Table 5
Hierarchical ranking of each morphometric parameter, the compound parameter and priority ranking for sub-watersheds SW13 to SW14.

ID	Parameters	Computed parametric ranks											
		SW13	SW14	SW15	SW16	SW17	SW18	SW19	SW20	SW21	SW22	SW23	SW24
1	Mean bifurcation ratio (R_{bm})	19	10	2	5	18	1	14	7	15	21	23	22
2	Mean stream length ratio (R_{lm})	10	22	23	1	5	24	19	2	7	16	9	3
3	Stream frequency (F_s)	19	20	21	22	13	10	6	12	17	15	23	3
4	Drainage density (D_d)	11	12	10	7	8	9	6	5	4	3	2	1
5	Drainage texture (D_t)	16	15	12	14	20	17	19	21	22	18	24	23
6	Length of overland flow (L_o)	14	13	15	18	17	16	19	20	21	22	23	24
7	Drainage intensity (D_i)	14	13	16	19	17	15	18	20	22	21	24	23
8	RHO coefficient (ρ)	4	9	19	20	10	24	7	16	11	3	2	5
9	Infltration number (I_f)	11	12	10	7	8	9	6	5	4	3	2	1
10	Relief (B_h)	10	15	22	14	12	17	23	21	20	24	19	18
11	Relief ratio (R_h)	1	16	22	14	3	10	23	20	17	24	5	2
12	Relative relief (R_{hp})	7	16	22	13	11	15	23	21	19	24	20	10
13	Ruggedness number (R_n)	4	17	22	5	3	12	24	8	6	23	2	1
14	Circulatory ratio (R_c)	4	6	21	13	3	11	14	8	7	20	1	5
15	Mean bifurcation ratio (R_{bm})	12	11	10	9	8	7	6	5	4	3	2	1
16	Mean stream length ratio (R_{lm})	13	14	15	16	17	18	19	20	21	22	23	24
17	Stream frequency (F_s)	12	11	10	9	8	7	6	5	4	3	2	1
18	Drainage density (D_d)	21	19	4	12	22	14	11	17	18	5	24	20
Compound parameter (Cp)		11.22	13.94	15.33	12.11	11.28	13.11	14.61	12.94	13.28	15.00	12.78	10.39
Ranking		13	14	15	16	17	18	19	20	21	22	23	24
Final priority		High	Low	Low	Medium	High	Medium	Low	Medium	Medium	Low	Medium	High

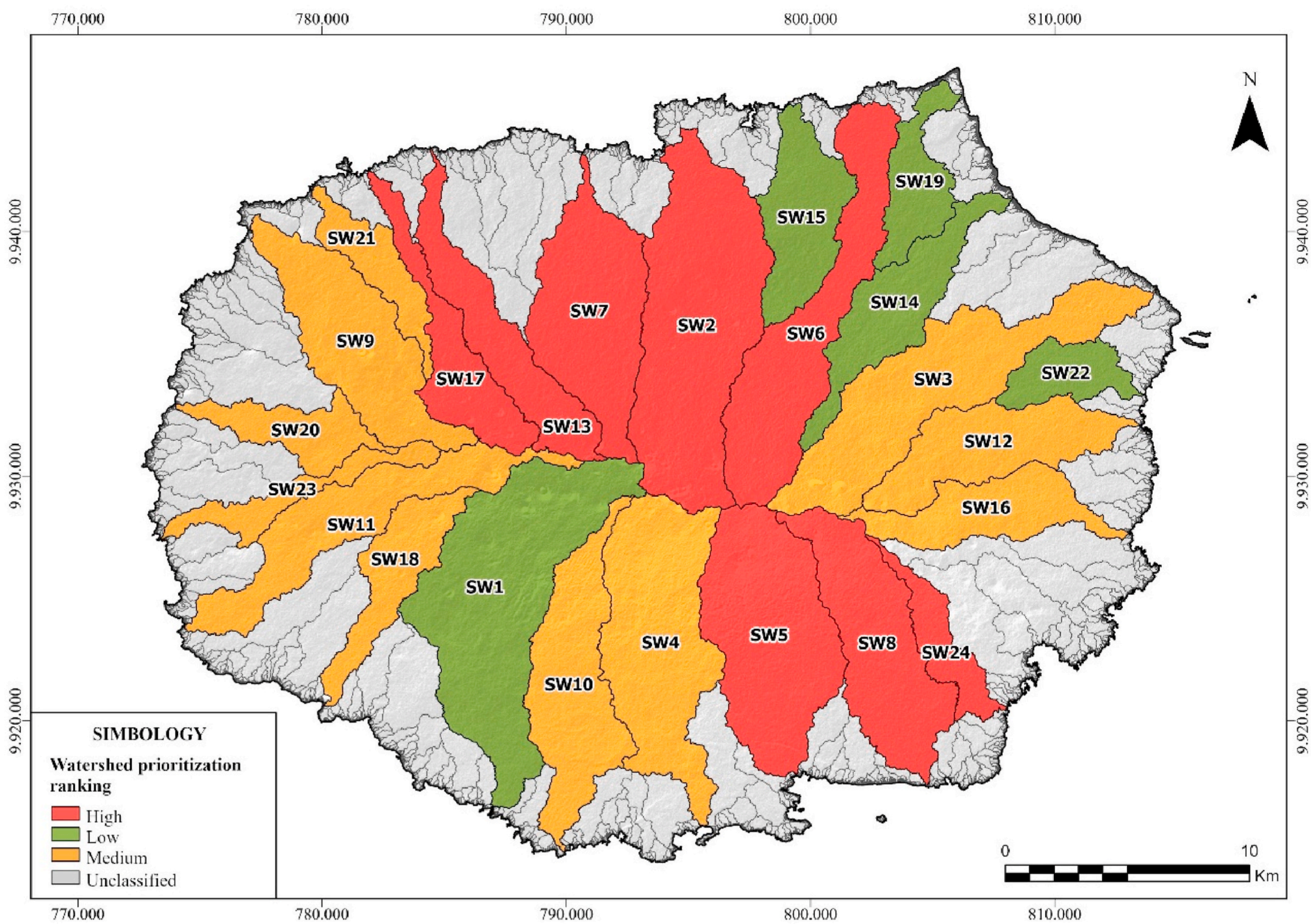

Fig. 7. Sub-watershed prioritization ranking for Santa Cruz Island, classified into three categories: high, medium, and low priority. This classification reflects the relative susceptibility of each sub-watershed to surface runoff and erosion based on morphometric analysis.

overwhelmed by infectious diseases, and recurrent droughts causing acute water shortages. These structural vulnerabilities significantly limited the island's capacity to implement immediate and effective mitigation measures prior to the cyclone. The severe impact of Cyclone Chido and the subsequent storm Dikeledi further worsened existing vulnerabilities, leading to extensive flooding, loss of life, and destruction of informal settlements primarily inhabited by the most vulnerable populations. The governmental response, though involving emergency reconstruction plans, has been criticized for insufficiently addressing the island's long-standing socio-economic and infrastructural challenges, particularly those affecting undocumented immigrants.

In this context, the present study shows that hydro-geomorphological characterization and the prioritization of sub-watersheds based on their susceptibility to erosion not only improve the understanding of watershed dynamics but also provide fundamental tools for defining targeted management actions. This methodology directly supports the objective of strengthening water security and territorial resilience in the face of climate threats and growing demographic pressures. It is important to note that while morphometric parameters offer valuable insights into watershed behavior, their use alone may not capture all hydrological complexities. For instance, temporal variations in precipitation, land cover changes, and groundwater interactions require integration in future studies to improve prioritization accuracy. Additionally, local socio-economic factors influencing water use and land management should be incorporated to enhance decision-making relevance.

Furthermore, the prioritization results obtained in this study allow decision-makers to identify the most erosion-prone sub-watersheds, guiding the implementation of early interventions in areas with higher environmental vulnerability. By integrating morphometric parameters that reflect both the physical characteristics of the terrain and its hydrological behavior, the analysis supports a proactive approach to watershed management. This enables the design of sustainable strategies focused on water conservation, risk mitigation, and long-term planning, crucial components for ensuring the well-being of island communities that depend on limited and sensitive water resources.

In this regard, the prioritization of sub-watersheds provides not only a scientific basis for soil and water conservation strategies but also a valuable input for agricultural planning. Identifying areas less prone to erosion and with higher water retention can inform decisions about the localization of agricultural activities, the type of crops suitable for each sub-watershed, and the implementation of agroecological practices that align with the island's natural hydrological dynamics. Future research should focus on incorporating multi-criteria decision analysis frameworks, coupling morphometric data with socio-economic and ecological parameters to create holistic watershed management plans. The use of remote sensing time series and field-based hydrological monitoring can further validate and refine prioritization models, thus enhancing adaptive management in the face of climate variability and human pressures.

5. Conclusion

The morphometric prioritization of the 24 watersheds on Santa Cruz Island revealed significant variability in susceptibility to erosion. Watersheds such as SW7, SW5, SW24, SW6, SW13, SW8, SW17, and SW2, which obtained the lowest Composite Parameter (C_P) scores, exhibit greater geomorphological vulnerability, positioning them as critical zones requiring immediate intervention. These areas demand targeted soil conservation and water management strategies (such as reforestation, construction of small-scale check dams, and slope stabilization) to safeguard ecosystem services, reduce runoff and sedimentation risks, and maintain soil productivity (especially in areas where agricultural activities are present or planned).

In contrast, watersheds like SW15, SW22, SW19, SW1, and SW14 (ranked with higher C_P values) present more favorable morphometric and hydrological conditions, indicating greater resilience and lower priority for immediate mitigation. The rural areas within SW1, for example, show potential for sustainable agricultural development and rainwater harvesting systems, given their higher retention capacity and reduced susceptibility to erosion. We recommend promoting water-efficient agricultural practices in these areas, such as drip irrigation or agroecological approaches that align with the island's hydrological patterns.

The remaining watersheds are located primarily within the Sustainable Use Zone (SUZ), where any potential development or water use would require the appropriate permits from the Dirección del Parque Nacional Galápagos (DPNG), a dependency of the Ministerio del Ambiente, Agua y Transición Ecológica (MAATE). Therefore, coordinated planning with environmental authorities is essential to ensure that any interventions aling with conservation goals and local regulations.

This prioritization framework constitutes a crucial tool for decision-making in integrated watershed management, particularly within ecologically sensitive island environments. It enables strategic allocation of technical and financial resources, avoiding inefficient uniform interventions and allowing for focused action in erosion-prone zones. Furthermore, watersheds classified as low priority, such as SW22 and SW1, emerge as promising candidates for sustainable water harvesting and agricultural planning. To validate their suitability, additional structural assessments, soil sampling, and geochemical analyses are required. To validate their suitability, we recommend complementary field assessments, including structural evaluations, soil characterization, and geochemical water quality analyses. Supported by GIS, DEM-based modeling, and photogrammetry, this integrative approach narrows the search area for viable water sources and enhances the resilience of water systems while minimizing unnecessary environmental and economic costs.

Beyond the specific case of Santa Cruz, this methodological framework offers a transferable tool for morphometric watershed prioritization in other volcanic island settings facing similar socio-ecological pressures. Its application can inform integrated land and water management in territories with limited freshwater resources, steep topography, and sensitive ecosystems. However, this study has certain limitations, including reliance on morphometric parameters alone, without direct incorporation of climatic variability, land cover data, or hydrogeological measurements. These factors, while partly inferred, should be integrated into future work to enhance the precision and applicability of prioritization efforts. Future studies may expand on this approach by integrating time-series precipitation data, remote sensing–derived vegetation indices, and field-based hydrogeological surveys to support multi-criteria decision-making and dynamic watershed modeling.

CRediT authorship contribution statement

Rosado Victoria: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bravo Gianella:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Vaca Valeria:** Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization. **Menoscal Menoscal Melanie:** Software, Methodology, Data curation, Conceptualization. **Garces Daniel:** Writing – review & editing, Writing – original draft, Supervision, Resources, Funding acquisition, Conceptualization. **Larreta Erwin:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Mulas Maurizio:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2025.100843.

Data availability

Data will be made available on request.

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