

UAV-based Hydrological Analysis for Integrated Water Management: NbS for Surface Water Storage

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Abstract

In the coastal regions of Ecuador, seasonal rainfall regime and limited access to water infrastructure have led to interest in traditional water-harvesting systems, such as artificial wetlands (albarradas). However, the locations of these structures are often selected empirically rather than through hydrological analysis. The study seeks to identify potential sites for albarradas as Nature-Based Solutions (NBS) by integrating unmanned aerial vehicles (UAVs) and hydrological analysis to strengthen integrated water management in water scarcity areas. The methodology encompassed: i) UAV photogrammetry to capture high-resolution aerial images (4.84 cm/pixel) and generate a digital elevation model (DEM); ii) stormwater runoff simulation using HEC-RAS to determine flow direction and accumulation; and iii) identification of albarrada sites for rainwater harvesting. Two accumulation basins with maximum depths of 1.5 m were identified, located 70 m from the coastline and 3.7 m above sea level. Two dams with preliminary dimensions were proposed for these locations, each with a storage capacity of 280 m³. The proposed approach provides a reproducible framework for planning water management strategies using Nature-Based Solutions (NBS) in information-limited rural environments, supports local decision-making, and guides upcoming investments in climate-resilient water infrastructure in coastal and semi-arid regions.

Keywords

UAV, HEC-RAS, Rainwater Harvesting (RWH), Hydrological modelling, Water sustainability, Geoinformatics

1. Introduction

Water security is one of the main challenges facing rural communities in coastal and semi-arid regions, where climate variability, rainfall seasonality, and limited supply infrastructure hinder sustainable access to water [1]. In these biomes, groundwater abstraction becomes essential to the sustainable development of communities. In this context, Nature-based Solutions (NbS) have emerged as promising strategies for improving water availability by restoring or harnessing natural hydrological processes [2]. These solutions include traditional water-harvesting and storage systems, such as artificial wetlands

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(‘albarradas’), an ancestral technique developed by local communities and used in several regions to store runoff and promote aquifer recharge [3].

These techniques are not limited to rural communities; studies such as [4] propose reservoirs and a dyke as Water Sowing and Harvesting (WS&H) strategies to reduce water deficits and support continuity of production in a poultry sector facing water-supply constraints in semi-arid areas. Studies conducted in Kenya [5], India [6], and Ethiopia [7] have shown that retention and recharge structures can increase water availability during the dry season, strengthen irrigation supplies, and improve farmers’ productivity and incomes. These cases demonstrate that, while retaining their ancestral and community value, such techniques can be adapted to contemporary production contexts and contribute to greater water resilience, supply security, and the sustainability of economic activities.

In Ecuador, NbS form part of the ancestral knowledge of WS&H, whose configuration varies according to the climatic, topographic, and geological conditions of each region. Among the various recorded techniques are albarradas, artisanal dykes (locally known as tapes), cochas, tajamares, and camellones [3]. This type of infrastructure is implemented in Ecuador to optimize the availability and use of water resources for community supply and agricultural production. For example, in Paltas-Catacocha (Loja), the restoration of cochas and tajamares enabled water to be regulated and retained in aquifers while reactivating ecological functions and human activities [8]. In Manglaralto (Santa Elena), the combined use of albarradas, technical-artisanal dykes and community management has contributed to runoff storage, artificial aquifer recharge, saline-intrusion control and continuity of supply during the dry season [9].

However, the planning of these structures is still largely based on empirical knowledge, which may limit their efficiency and hinder their integration into water-management strategies at the territorial scale. NbS have commonly been addressed within ecological engineering [10] and soil and water bioengineering [11]. Recent studies such as [12, 13] question the conventional fields of knowledge that currently predominate in NbS research and advocate a transdisciplinary approach incorporating areas such as geoscience, health, and economics to maximize the sustainable potential of NbS in water-resource stewardship. In this regard, integrating geospatial tools and hydrological models can optimize technical

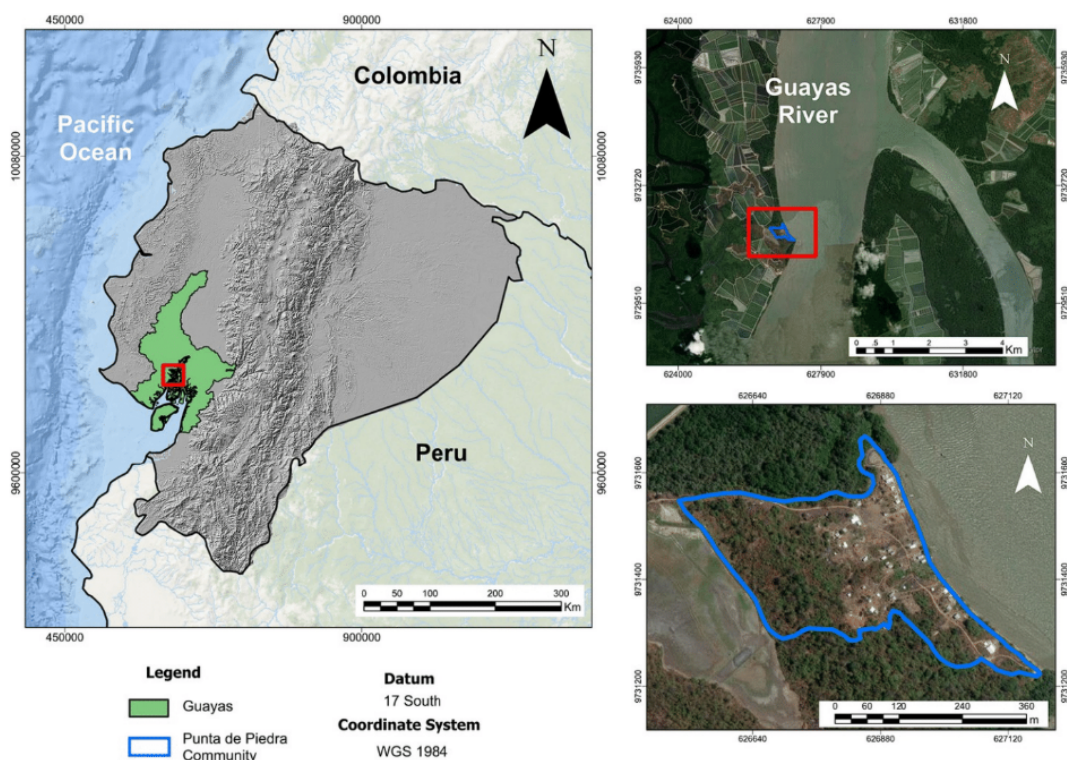


Figure 1: Geographic Location of Punta de Piedra.

design and identify areas with high rainwater-harvesting potential [14]. In particular, unmanned aerial vehicles (UAVs) have emerged as key technologies because they generate high-resolution digital elevation models, enabling precise analysis of topography, surface-flow direction, and runoff patterns [15]. These tools create new opportunities to integrate detailed topographic information with hydrological models and support the planning of water-harvesting infrastructure based on natural processes.

Punta de Piedra is a coastal community located in the Gulf of Guayaquil in Ecuador (Figure 1) and is highly dependent on groundwater because it lacks drinking-water services and rainwater-harvesting structures. However, the existing wells are close to the coastline and were constructed without technical criteria, making these water sources highly vulnerable to saline intrusion. Accordingly, this study proposes albarradas as NbS that could serve as green infrastructure for capturing freshwater as an alternative to groundwater sources and as a filtration medium for recharging the aquifers that supply hand-dug wells.

In this context, the following research question is posed: How can integrating UAV photogrammetry and hydrological analysis identify potential areas for locating NbS in water-scarce coastal environments? This study aims to identify strategic locations for albarradas as NbS by integrating UAV photogrammetry and hydrological analysis, thereby contributing to integrated water management in water-scarce coastal territories.

2. Materials and Methods

This study presents a methodological framework that integrates geospatial analysis using UAVs with surface-hydrology assessment to propose NbS for surface-water storage (Figure 2) and support integrated water management in data-scarce coastal environments. The methodological framework comprises three phases: (i) topographic surveying using UAV photogrammetry; (ii) hydrological analysis and rainfall-runoff simulation using HEC-RAS; and (iii) identification and proposal of NbS based on traditional rainwater-harvesting systems (“albarradas”).

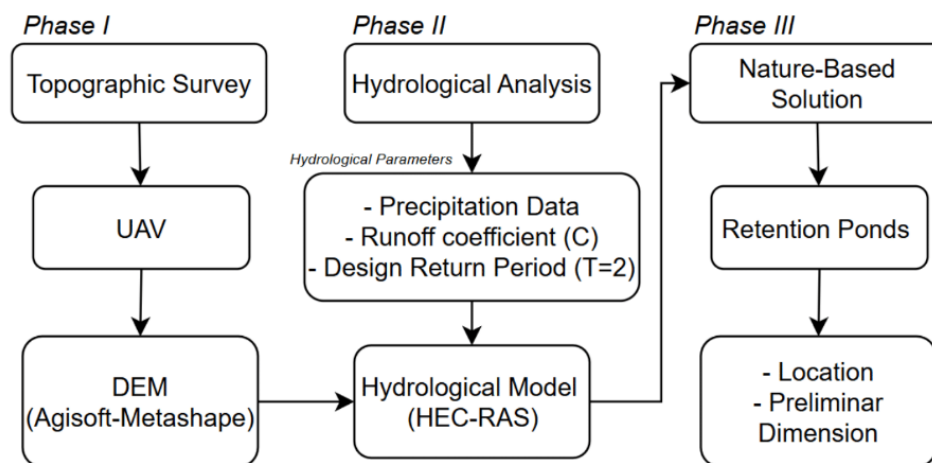


Figure 2: Methodological framework.

2.1. Phase I: UAV photogrammetry

A high-resolution topographic survey was undertaken using an unmanned aerial vehicle (UAV), specifically a DJI Mavic 2 Pro. The flight was planned to use DroneDeploy version 5.48.1, with a flight altitude of 20 m above ground level and seven ground control points (GCPs) distributed uniformly across the study area to improve the geometric accuracy of the final products [16].

The GCPs were georeferenced using Differential Global Positioning System (DGPS) observations following the Real-Time Kinematic (RTK) method. Corrections were obtained through a station operated

by Ecuador's Military Geographical Institute (IGM, acronym in Spanish) [17]. The acquired images were processed in Agisoft Metashape Professional v1.8.4 to generate a dense point cloud, an orthomosaic, and a high-resolution digital elevation model (DEM).

2.2. Phase II: Rainfall-runoff simulation (HEC-RAS)

Hydrometeorological information was obtained from the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) satellite product, which provides quasi-global precipitation estimates at high spatial and temporal resolution [18]. The maximum daily precipitation value recorded in each year was selected to form an annual-maxima series. A frequency analysis was then performed by fitting a lognormal distribution, from which a 24 h design rainfall depth of 147.74 mm was estimated for a 2-year return period. This return period was selected because it represents a frequent event suitable for the preliminary assessment of small runoff-harvesting and storage structures [19, 20]. Rainfall depths for shorter durations were derived using the Dyck and Peschke relationship [21]:

$$P_D = P_{24} \left(\frac{D}{1440} \right)^{0.25} \quad (1)$$

where P_D is the accumulated precipitation for a duration D , expressed in minutes, and P_{24} is the 24 h design precipitation. This procedure yielded rainfall depths of 66.75 and 104.47 mm for durations of 1 and 6 h, respectively. Each depth was then distributed temporally at 10 min intervals using the alternating-block method, producing the hyetographs used as inputs to HEC-RAS. Rainfall-runoff simulations were performed using the Hydrologic Engineering Center's River Analysis System (HEC-RAS), version 6.5 [22].

A 2D area boundary condition line was defined along the coastline, and cover parameters were introduced according to the Soil Conservation Service Curve Number (SCS-CN) method (Table 1). The parameters were selected according to the U.S. Department of Agriculture Soil Conservation Service [23].

Table 1

Curve Number (CN) selected from the equivalence between the land cover conditions in the study area and the hydrological classification provided by the USDA Soil Conservation Service.

Land Cover (HEC-RAS model)	Equivalence at US-ACE-NRCS classification	Treatment or practice	Hydrological Condition	Soil Hydrological Group (HSG) "C"	CN adopted
Vegetation	Woods	-	Fair	73	73
Orchards	Row crops	Straight row	Good	85	85
Bare Soil	Fallow	Bare Soil	-	91	91

Terrain-derived parameters, including flow direction, flow accumulation, drainage patterns, and catchment boundaries, were extracted from the DEM using ArcGIS and incorporated into the hydrological model. The simulation results enabled the identification of preferential runoff corridors and natural flow-convergence zones suitable for rainwater-harvesting interventions.

2.3. Phase III: NbS proposal

Based on the hydrological simulation results, strategic locations were identified for proposed albarradas as NbS for rainwater harvesting and surface-water storage. Site selection considered topographic depressions, runoff-concentration zones, and storage feasibility. Maximum depths and topography were considered when proposing the dimensions of the albarradas. The simulation period extended beyond the rainfall duration to represent the recession phase and determine when water levels began to decline. This criterion represents the complete hydrological response because the maximum hydraulic response may occur after rainfall has ended [24].

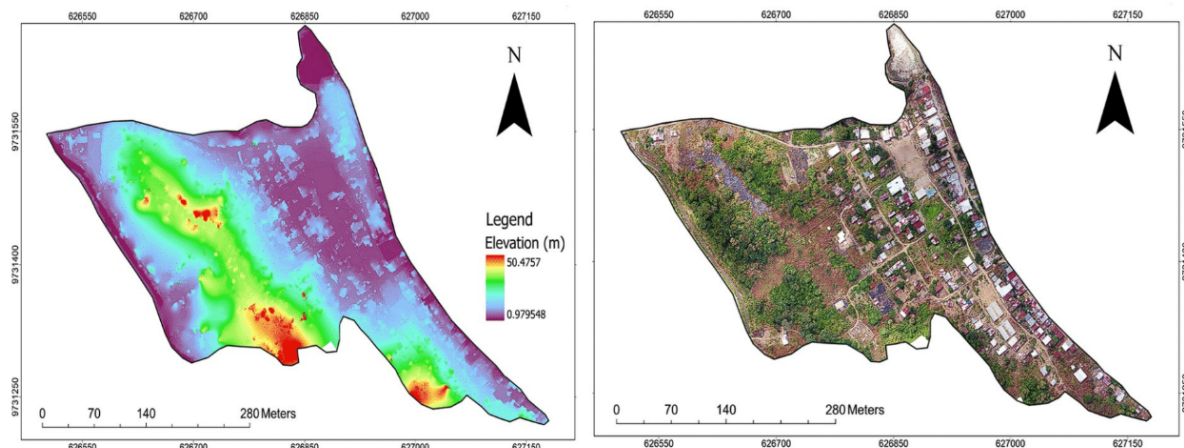


Figure 3: UAV-derived digital elevation model of the study area.

3. Results and Discussion

3.1. UAV-derived topographic products

The UAV survey generated a 2.5 cm/pixel orthomosaic and a 4.84 cm/pixel DEM (Figure 3). Both products show that the higher-elevation areas east of the community have lower urban density and more vegetation, whereas the lower-elevation areas to the west have greater urban density. The imagery also shows small-scale crops associated with household gardens and homes established along the riverbank because residents depend on fishing and use river water for domestic activities.

3.2. Terrain and drainage-network analysis

Figure 4 shows a drainage network, revealing how surface runoff converges south of the community. The analysis identified three catchments. Catchment 1, covering 1.43 ha, is the largest and receives flow from several drainage channels; however, it is influenced by the slope of the existing footpath. Catchment 2 covered 0.35 ha, and its outlet was located in undeveloped land, whereas catchment 3 covered 0.40 ha and drained toward nearby homes and undeveloped plots. The results showed that anthropogenic land modifications altered natural runoff routes and the configuration of the drainage network. This behaviour is consistent with the findings of Buchanan et al. [25], who demonstrated that drainage networks alongside roads can increase hydrological connectivity, alter natural flow routes, and reduce the transport distances to receiving channels.

3.3. Rainfall-runoff simulation

Figure 5 presents the hydrological simulation for three rainfall scenarios (1, 6, and 12 h). Flow concentrations at 6 and 12 h remained nearly constant, supporting the identification of these areas as design water-accumulation basins. Accumulation occurred along the topographic depressions identified in the DEM analysis, west of the community. The elevated areas to the east generated comparatively less flow accumulation.

The simulated water depths reached their highest values (1.49–9.21 m) in areas adjacent to a shrimp farm because the software interpreted the embankments of these structures as flood-prone areas. The remaining inundation basins were located in the northern part of the community, with maximum depths ranging from 0.26 to 1.48 m.

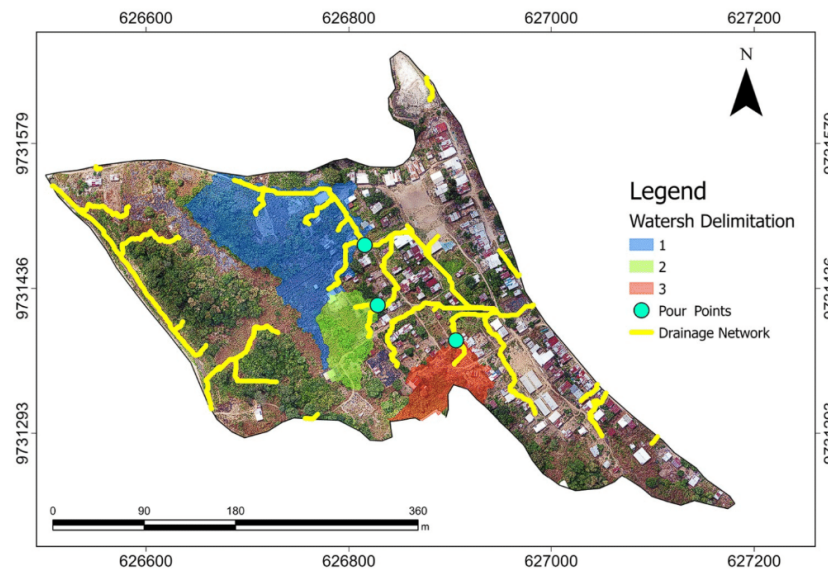


Figure 4: Flow accumulation and drainage network extracted from the UAV-derived DEM.

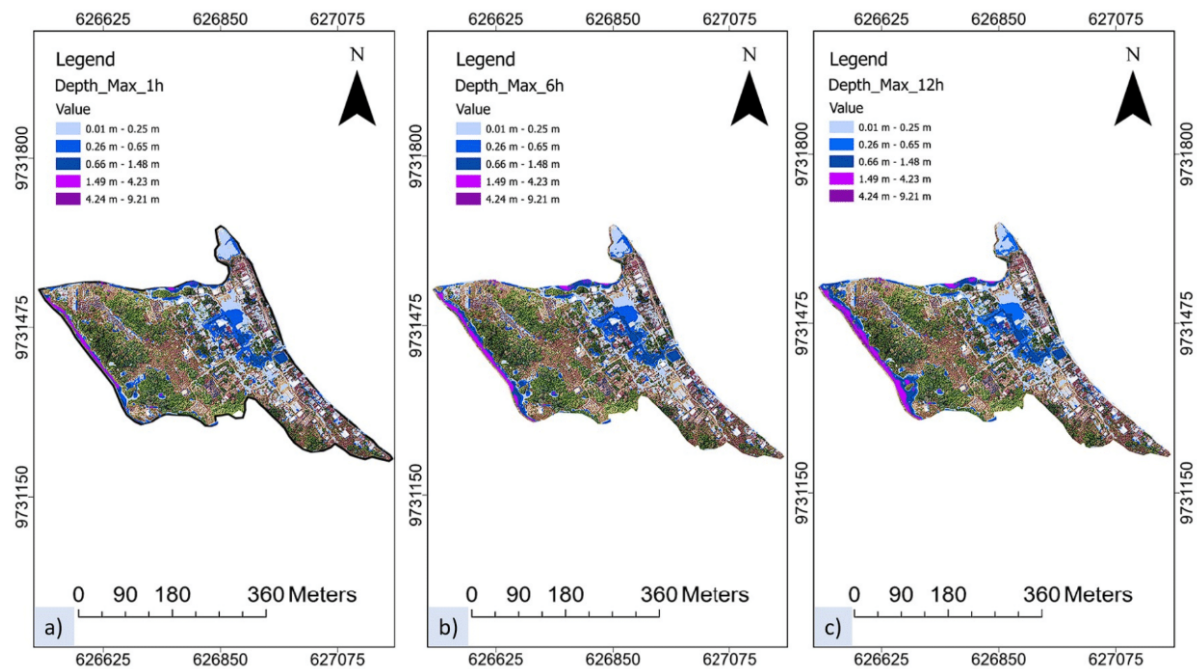


Figure 5: Simulated maximum surface-water accumulation depths obtained from HEC-RAS under design rainfall events of: (a) 1 h, (b) 6 h, and (c) 12 h.

3.4. Identification of suitable NbS locations

The rainfall-runoff simulation identified two potential locations for artificial wetlands. These sites were characterized by convergent runoff, depths of 1.00–1.49 m, and available storage space based on land occupancy, assessed by visual inspection of the orthophoto. The artificial wetlands are oriented northwards, with a 10 m east-west cross-section (Figure 6), and each proposed structure extends 15 m northwards. This geometry corresponds to a storage capacity of 280 m³, which could supply between 186 and 220 inhabitants for one month, based on the Ecuadorian regulatory reference allowance of 85 L/person/day for rural communities. The maximum modelled depth informed a proposed reference height of 2.5 m, with a freeboard of 0.3 m to prevent overtopping and local flooding.

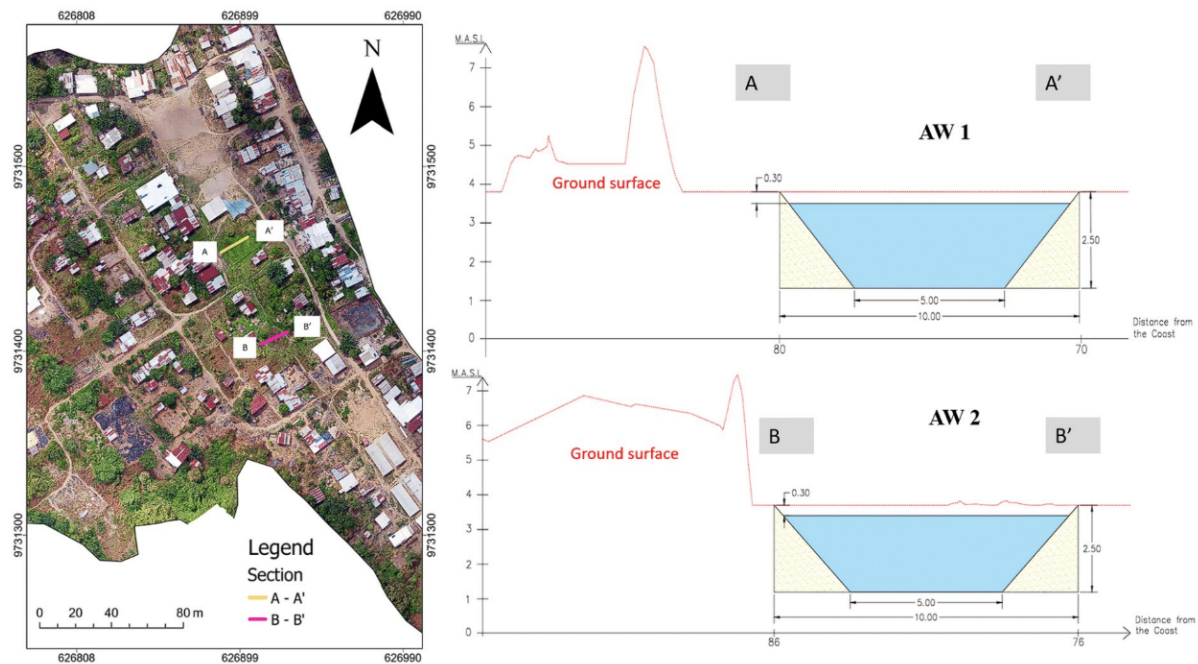


Figure 6: Proposed locations of artificial wetlands (“albarradas”) based on runoff convergence areas.

3.5. Limitations and Future Research Directions

The main contribution of this study is integrating high-resolution UAV photogrammetry with two-dimensional hydraulic modelling to identify local runoff-convergence zones and propose preliminary locations for albarradas in a data-scarce coastal community. Unlike experiences in Manglaralto [9] and Paltas-Catacocha [8], where Water Sowing and Harvesting techniques have been consolidated primarily through ancestral knowledge, community management, and hydrogeological assessment [3], the approach applied in Punta de Piedra explicitly incorporates terrain microtopography and the spatial response to 1, 6, and 24 h rainfall events to provide a technical basis for site selection. It is also related to the AVISID case [4], where HEC-RAS was used to identify retention areas and propose reservoirs and dykes to reduce a production-related water deficit. However, the present study focuses on smaller excavated structures for decentralized storage in a rural setting. The results also show cultivated plots, on which the community probably depends for food. Therefore, conserving water through the proposed artificial wetlands could help strengthen regional food security. This potential to enhance agricultural capacity has been demonstrated in India [6], where water-retention dykes contributed to local recharge and irrigation-water supply in drought-prone communities.

One limitation of the study is the exclusive use of CHIRPS satellite precipitation data because continuous rain-gauge records are unavailable for the area. Although this product represents spatial and seasonal patterns, its accuracy may vary with temporal scale and local conditions. In the Ambato River basin, Ecuador, CHIRPS showed a lower capacity to detect daily events and differences in performance among stations [26]. Similarly, biases and overestimation associated with topography and the limited availability of reference stations were identified in the central Andes of Argentina [27]. The results should therefore be interpreted as regional estimates and validated in future studies using local rain gauges and intensity-duration-frequency (IDF) curves. On the other hand, for the selection of hydrological soil groups, visual field identification provides only a practical first approximation of soil conditions, but it introduces uncertainty into the assignment of hydrologic soil groups. ASTM D2488 [28] recognises visual-manual procedures as suitable for preliminary soil identification but recommends laboratory procedures when precise classification is required. Therefore, limit and permeability studies will be required in future research. Furthermore, the model was not calibrated against discharge or depth measurements, and the proposed capacities are conceptual estimates that do not yet account

for actual evaporation and infiltration losses, water-table fluctuations, salinity, or ground geotechnical conditions. Future research should therefore include field hydrometeorological monitoring, infiltration and soil-stability tests, seasonal groundwater monitoring, sensitivity analysis of hydraulic parameters, and validation of stored volumes using reference areas and post-event surveys. These steps are required to advance from the identified locations to final designs and assess their effective contribution to water supply and aquifer recharge.

4. Conclusion

This study demonstrated that in Punta de Piedra, a coastal community in Ecuador with limited data availability, UAV photogrammetry, GIS-based terrain analysis, and HEC-RAS two-dimensional modelling can be applied to identify potential sites for rainwater storage using nature-based solutions (NbS). The UAV survey produced an orthomosaic at 2.5 cm/pixel and a digital elevation model at 4.84 cm/pixel, allowing the delineation of three micro-watersheds and the identification of runoff pathways controlled by both natural topography and anthropogenic land modification.

Simulations of 1, 6, and 24 h design rainfall events showed areas of surface-water accumulation, from which two sites were selected as preliminary locations for artificial wetlands. A gross storage capacity of approximately 280 m³ per site was proposed, equivalent to a combined capacity of 560 m³. In theory, this volume could meet the monthly domestic demand of approximately 220 inhabitants, based on a reference allowance of 85 L/person/day and without deducting evaporation, infiltration, dead storage or treatment requirements. The principal contribution of the study is an integrated procedure based on UAV photogrammetry, geospatial analysis and 2D hydraulic modelling to identify and prioritize potential rainwater-storage sites in coastal communities with limited data availability. The results provide a preliminary assessment to support decision-making in response to the water supply needs of coastal communities. These sites could be configured as a solution that guarantees access to water resources and ensures food security for the community.

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Declaration on Generative AI

During the preparation of this work, the authors used Grammarly for grammar and spelling checks. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication’s content.

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