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Evaluation of the Hydrological Response to Land Use Change Scenarios in Urban and Non-Urban Mountain Basins in Ecuador

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Abstract: Land cover is a crucial factor in controlling rainfall–runoff processes in mountain basins. However, various anthropogenic activities, such as converting natural vegetation to agricultural or urban areas, can affect this cover, thereby increasing the risk of flooding in cities. This study evaluates the hydrological behavior of two mountain basins in Loja, Ecuador, under varying land use scenarios. El Carmen small basin (B1), located outside the urban perimeter, and Las Pavas small basin (B2), within the urban area, were modeled using HEC-HMS 4.3 software. The results highlight the significant influence of vegetation degradation and restoration on hydrological processes. In degraded vegetation scenarios, peak flows increase due to reduced soil infiltration capacity, while baseflows decrease. Conversely, the conserved and restored vegetation scenarios show lower peak flows and higher baseflows, which are attributed to enhanced evapotranspiration, interception, and soil water storage. The study underscores the importance of ecosystem management and restoration in mitigating extreme hydrological events and improving water resilience. These findings provide a foundation for decision-making in urban planning and basin management, emphasizing the need for comprehensive and multidisciplinary approaches to develop effective public policies.

Keywords: land use change; hydrological modeling; HEC-HMS; urban sprawl; natural forest; mountain basins

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1. Introduction

Environmental elements such as vegetation cover, climate, topography, and soil are key factors controlling rainfall–runoff processes in Andean basins [1,2]. However, anthropogenic pressure on the Andean basins is growing due to population growth. For example, Arteaga et al. (2022) stated that anthropogenic activities causing land degradation are the main drivers of soil erosion and increasing dam sedimentation [3]. Native land cover types play a fundamental role in regulating the hydrological cycle. This has been demonstrated in several studies on the effects of converting forests to different agricultural, livestock, or urban uses [4]. As a result of these conversions, hydrological processes as well as water quality and quantity are significantly affected [5,6].

Changes in land use/land cover (LULC) also modify the physicochemical properties of the Andean soils [7], such as hydraulic conductivity and density, leading to an increase in surface runoff during intense precipitation events [8]. Quichimbo et al. (2017) found that land use change, specifically afforestation with *Pinus patula* and *Eucalyptus globulus* plantations, changes Andean soil properties, leading to a sharp decrease in water production and the water regulation capacity of small basins [9,10]. The degree of soil degradation in a basin is correlated with the land use intensity, which can be measured by livestock density

or cultivation techniques [10]. Arteaga et al. (2020) identified priority areas for integrated management of semiarid basins in the Ecuadorian Andes, mainly to promote groundwater recharge and improve baseflow [11].

Significant deforestation processes are occurring across all Andean basins, mainly in those that drain into the Amazon basin, which still preserves forest remnants with good-quality wood [12]. This large basin lost approximately 12% (about 45 million hectares) of its native forest from 1985 to 2021, which was largely replaced by agricultural land [13]. In Ecuador, similar dynamics have been observed, despite the political strategies and incentives implemented after the "Agrarian Reform" in the 1960s to ensure a more equitable distribution of land. These strategies have not reversed the trend, and forest loss continues at an alarming rate [14]. González et al. (2016) report that deforestation in Ecuador has increased consistently, from −0.9% in 1986–2001 to −1.9% in 2001–2008 [12].

One of the local factors contributing to deforestation processes is the rapid growth of the urban and rural population in recent years [15,16]. This phenomenon has led to the conversion of large areas of previously forested areas into agricultural and livestock zones [17]. The outlook is more critical for Ecuador because a large part of its population—close to 46%—is located in high mountain rural areas or water recharge areas. This creates significant pressure on natural ecosystems within buffer zones of protected areas [18], with 25% of accumulated deforestation occurring between 1990 and 2018. As a result, mountain basins with natural vegetation have been replaced by agriculture and urban infrastructure [19].

Considering this background, studying the effect of change in LULC on the hydrology of basins with different degrees of anthropic intervention is key to decision-making in inter-Andean cities. These conditions are present in Loja, an intermediate city in southern Ecuador. Loja has experienced the highest urban expansion in the Ecuadorian Andean valleys: 82% between 2001 and 2014 [16]. Additionally, Loja is home to peri-urban small basins such as El Carmen, which have shown positive changes in LULC in the last 15 years [20]. This small basin is one of the main water sources of the drinking water used for treatment and consumption in the city, and its conservation is essential to maintaining good water quantity and quality [5,21]. In contrast, other small basins as Las Pavas have undergone strong land use changes, specifically due to agriculture, livestock, and dispersed urban growth [15,22]. These strong land use changes have caused flooding under intense precipitation events in areas of high urban density.

Hydrological modeling has been conducted in small basins in southern Ecuador in other research using the flow duration curve [4,10]. The focus of these studies was to predict the hydrological responses of small basins to LULC change scenarios, but these studies were mainly oriented toward paramo ecosystems. In recent studies, meteorological and hydrological analysis have been initiated for small mountain basins, using the semi-distributed hydrological model HEC HMS, due to its flexible and easy-to-use interface, mainly for ungauged basins [8,21,23]. However, specific studies on the hydrological response in small basins with strong changes caused by urban growth are lacking.

Therefore, the main objective of this study is to evaluate the hydrological response of the two mentioned mountain basins using HEC HMS. This model has multiple applications, from runoff simulation to flood modeling, and is very useful for land and water resources management. Furthermore, this hydrological response will be analyzed under hypothetical scenarios of land use change, both positive and negative, i.e., what would happen to the hydrology of these basins if their land cover was conserved or degraded? These results can be useful for decision-making in inter-Andean cities, providing information necessary for planning, organizing, and developing the territory and proposing strategies for the integrated management of watersheds.

2. Materials and Methods

2.1. Study Area

This research was conducted in two small basins in the city of Loja, located in the inter-Andean valley of the southern Ecuadorian highlands (Figure 1). Both basins are

situated between the coordinates −3.972N, −79.263E and −4.065N, −79.136E. These are part of the upper basin of the Zamora River, which flows into the Amazon basin. The region exhibits strong altitudinal gradients of temperature and precipitation caused by local topography and trade winds predominantly coming from the East [8]. However, during the rainy season (December to April), the trade winds are frequently interrupted by westerly winds from the Pacific Ocean, generating intense convective storms over this inter-Andean valley [24]. The small basins of the city of Loja are located at altitudes ranging from 1880 to 3420 m a.s.l. The climate is Andean temperate with an average temperature ranging from 8 °C at the mountain ridge to 16 °C in the lowlands. Rainfall is bimodally distributed, with two annual peaks: the primary peak occurs in March and the secondary peak occurs in October [14]. Soils in the middle and upper elevations are mainly Inceptisols with higher organic matter content, while Entisols predominate in the lowlands [14]. The entire inter-Andean valley has undergone significant changes in vegetation cover since the 1960 "Agrarian Reform", and in recent years due to urban growth [16].

El Carmen small basin (B1) drains an area of 8.6 km^2 in an altitudinal range from 2315 to 3417 m a.s.l (Figure 1). It is located on the western foothills of the Eastern Cordillera of the Andes [8,25]. This small basin is one of the main sources of drinking water for the city of Loja [5]. It is also part of the buffer zone of the Podocarpus National Park (PNP). The predominant vegetation types are montane humid forest and shrubland paramo. The mean annual precipitation in these basins ranges from 900 mm in the lower areas to 2500 mm at the higher elevations [14]. The vegetation cover and hydrological conditions are generally good, as the land is owned by the local municipality, which has reforested areas lacking native vegetation cover in recent years [21]. However, the lower part of this small basin still faces anthropogenic pressures due to the presence of grazing lands.

Las Pavas small basin (B2) is located in the eastern foothills of the Western Cordillera of the Andes (Figure 1). It covers an area of 13.3 km^2 and has an altitudinal range from 2100 to 3050 m a.s.l., with average annual precipitation ranging from 700 mm in the lowlands to 1200 mm in the uplands. This basin drains into the Zamora River in the north-central part of the urban area of Loja. The lowland area of this small basin is under significant anthropogenic pressure, as only 5% of its area retains native vegetation cover. This area has experienced disordered and dispersed urban growth, which is characterized by low population densities as well as discontinuities in urban service infrastructure [16].

The Gravelius index of B1 and B2 are 1.51 and 1.9, respectively. These basins have oblong shapes, making them less prone to violent, rapid, high-magnitude flooding events during intense rainfall.

2.2. Hydrometeorological Data

Due to the strong relationship between precipitation and altitude in small mountain basins [14], the climate stations representative of the study basins were identified based on elevation and proximity criteria [26]. Precipitation data were obtained from seven stations: La Argelia automatic weather station (M033) of the National Institute of Meteorology and Hydrology of Ecuador (INAMHI); Jipiro, Ventanas, Villonaco, and Militar, which are all part of the weather station network of the Private Technical University of Loja (UTPL); and two El Carmen rainfall stations operated by FORAGUA office at the National University of Loja (UNL). All stations utilize tipping bucket electronic rain gauges, with an accuracy of 0.1 mm for the INAMHI and FORAGUA-UNL stations, and an accuracy of 25.4 mm for the UTPL stations.

From the data exploration of these stations, three representative precipitation events from the rainiest season (Figure 1) of 2016 were selected for analysis: 1–5 March (event 1), 11–12 April (event 2), and 23–27 May (event 3).

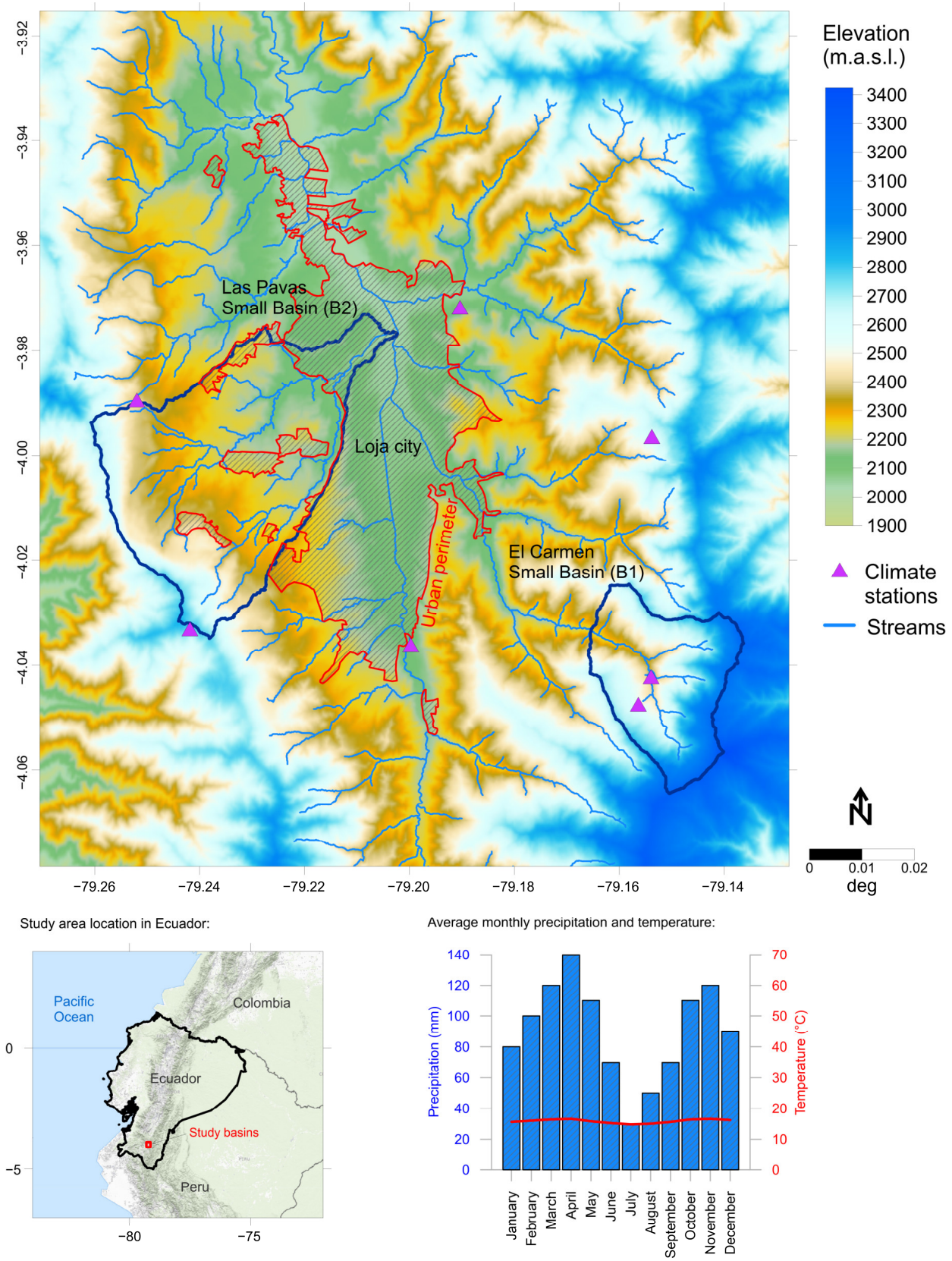

Figure 1. Location map and average monthly distribution of temperature and precipitation of the study area.

To validate the modeled discharge from these basins, gauged flow data were available only for B1. The observation instrument in B1 is equipped with a CAMPBELL automatic pressure sensor that measures the water level every 10 min. Empirical equations were used to convert water levels to discharge, based on direct flow measurements at various levels (rating curves) determined using chemical gauging methods [24].

2.3. Current and Hypothetical Land Cover Scenarios

A Sentinel-2 satellite image from 8 September 2023 was used to map the current land cover scenario (A). The image was obtained from the Copernicus Data Space Ecosystem (https://browser.dataspace.copernicus.eu/, accessed on 5 April 2024). The land cover maps (at a scale of 1:5000) were derived using the supervised classification algorithms of the QGIS Semi-Automatic Classification Plugin Version 8 [27].

To generate hypothetical land cover scenarios (B), the legends of the current land cover maps for each small basin were reclassified to represent land cover transformations. Given that the current scenario includes a conserved small basin (B1) and a degraded one (B2), hypothetical scenarios were constructed to represent the degradation of one and the restoration of the other.

These hypothetical future scenarios were developed to analyze the hydrological behavior of the basins in response to changes in their land cover attributes. The degradation scenario illustrates the fragmentation of native land cover resulting from deforestation and its subsequent reduction in water regulation capacity. Conversely, the restoration scenario depicts the recovery of water regulation capacity through the enhancement of native vegetation cover. This scenario is linked to the implementation of Sustainable Urban Drainage Systems (SUDSs) [28], which emphasize the integration of the water cycle in urban development.

2.4. Hydrological Modeling and Calibration

The hydrological modeling of the small basins was conducted using HEC-HMS v4.3 software (https://www.hec.usace.army.mil/software/hec-hms/downloads.aspx, accessed on 12 May 2024) [29]. This software enables the transformation of annual rainfall from selected years into discharge by integrating various hydrological methods [8,30]. The HEC-HMS model offers several methods for calculating total infiltration during a precipitation event and converting excess rainfall into runoff [31]. In this study, the Soil Conservation Service (SCS) curve number (CN) method was employed. Since its introduction in 1972, the CN method has become the most widely used approach for estimating runoff from rainfall due to its simplicity [8].

The CN method is associated with land use/cover and ranges from 1 to 100, depending on the degree of basin fragmentation. High CN values indicate high runoff and low infiltration (characteristic of degraded basins), while low CN values signify high infiltration rates and low surface runoff [8,29]. Due to the different LULC types found within the study's small basins, a weighted CN was calculated using the following Equation (1) [31]:

$$CN_W = \frac{1}{A_T}(A_{VC1} \times CN_1 + A_{VC2} \times CN_2 + \cdots + A_{VCN} \times CN_N) \quad (1)$$

where CN_W is the weighted curve number of the small basins, A_T is the total area of the small basins (km^2); $A_{VC1\text{-}N}$ is the area of the specific LULC type (km^2); $CN_{1\text{-}N}$ is the curve number for each LULC type.

To transform the effective precipitation into runoff, the SCS unit hydrograph transformation method was employed. This method requires the determination of the lag time (T_{LAG}) using the following Equation (2):

$$T_{LAG} = 2.587 \times L^{0.8} \times \frac{\left(\frac{1000}{WCN} - 9\right)^{0.7}}{(1900 \times S^{0.5})} \quad (2)$$

where T_{LAG} is the lag time (hours); L is the length of the small basin main channel (m); WCN is the weighted curve number; and S is the average slope (%).

To adjust the model in HEC-HMS, automatic optimization was performed by modifying the WCN and T_{LAG} parameters to achieve accurate flow simulation. More details of this process can be found in the work of Mejía et al. 2019 [8]. The hydrological model was validated using the Nash–Sutcliffe efficiency coefficient (NSE), which is one of the most widely used statistical methods for evaluating the efficiency of hydrological simulations [32].

3. Results

3.1. Hydrometeorological Information

Based on the precipitation data recorded by meteorological stations, three intense precipitation events of the rainy season were selected for the hydrological modeling of the basins (Figure 2).

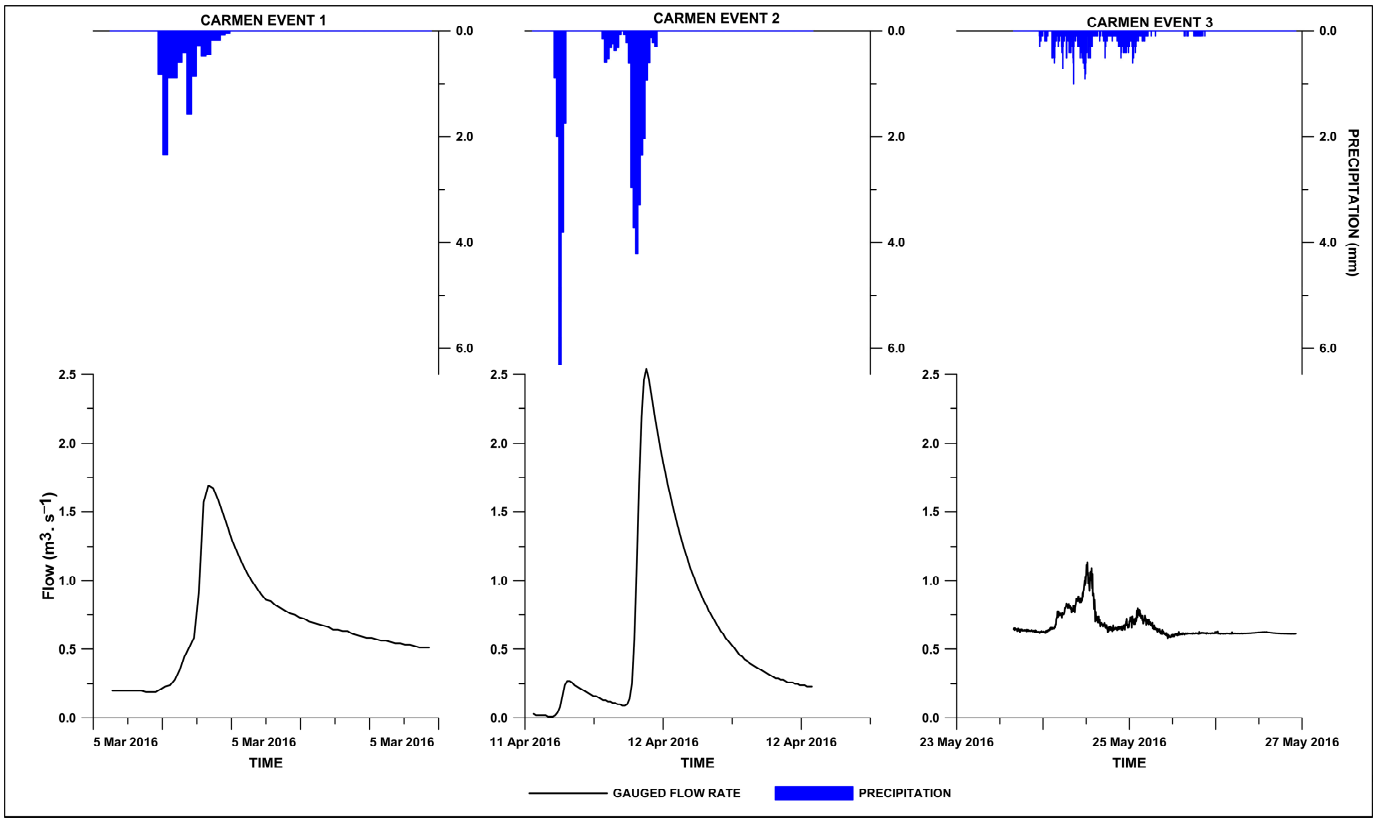

Figure 2. Selected precipitation events and hydrographs for hydrological modeling of the B1.

Of the small basins under study, the discharge curve was constructed for B1, as it is the only one equipped with the necessary instrumentation and data to convert water levels into flow rates. The discharge curve yielded a correlation value of $R^2 = 0.94$, indicating that the high, medium, and low flows measured are accurately represented. Consequently, the flows calculated during the study period at different levels using the curve equation closely reflect reality. The hydrograph displaying the resulting flows for B1 during the analysis period is shown in Figure 2.

3.2. Land Cover Scenarios

The attributes and proportions of land cover classes of the current and hypothetical future scenarios are shown in Table 1. Maps of these scenarios are shown in Figure 3.

Table 1. Hypothetical scenarios proposed for land use change.

Scenario	Small Basin	Current Land Cover Scenario (A)	Future Hypothetical Scenario (B)
a	B1 (El Carmen)	Native vegetation > 90%	Mixed land cover, deforestation (D) forest ≈ 30%, degradation ≈ 70%
b	B2 (Las Pavas)	Mixed (forest, crops, pasture, urban area)	mixed, restoration, SUDSs (R) restoration ≈ 70%, urban and other LULC classes ≈ 30%

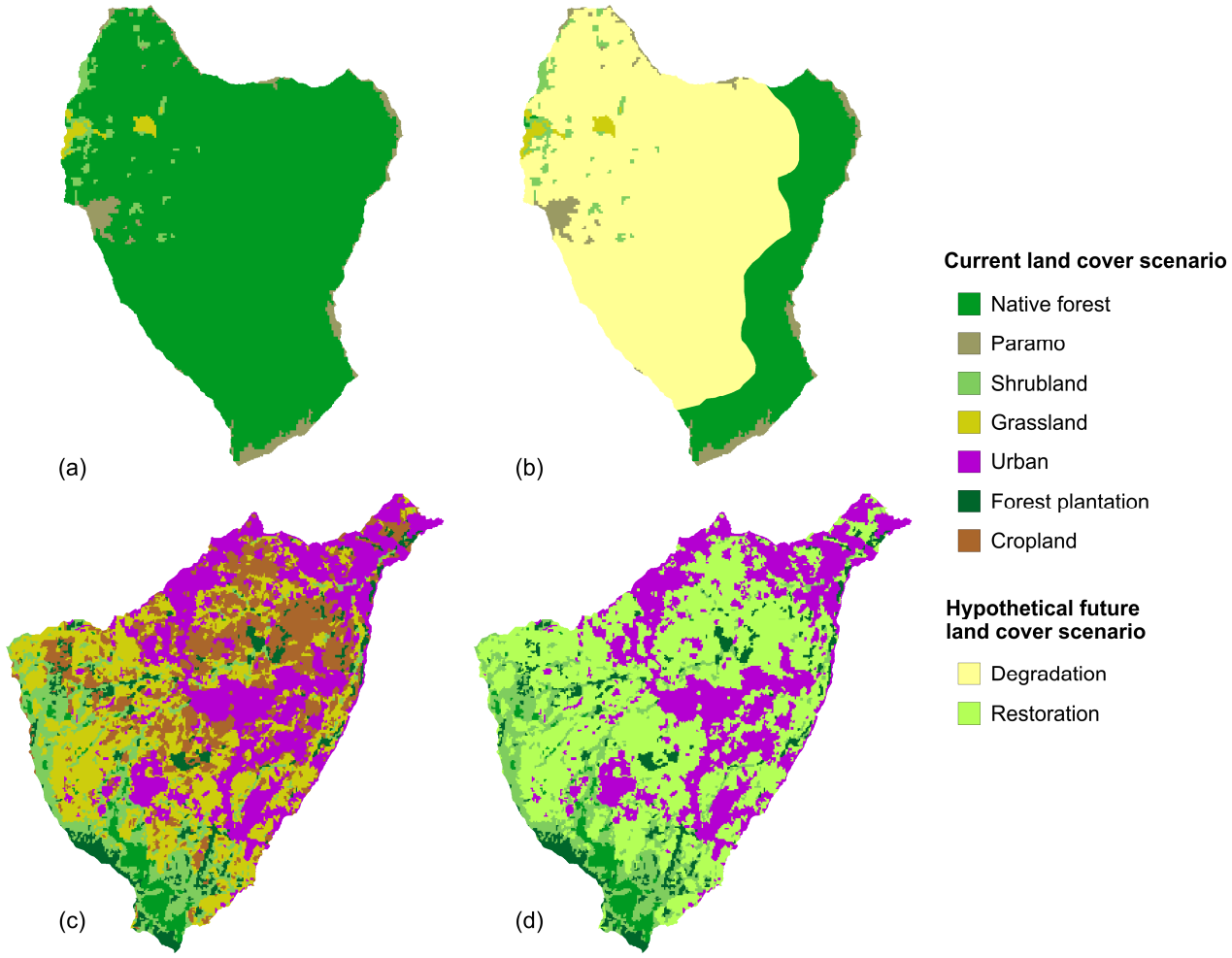

Figure 3. Current and future hypothetical land cover scenarios. (**a**,**b**) El Carmen (B1). (**c**,**d**) Las Pavas (B2).

As illustrated in Figure 3a, 90% of the B1 small basin area is currently covered by native forest. This proportion reflects the conservation practices implemented by the Municipality of Loja, primarily through reforestation campaigns with native tree species over the past 15 years [33]. Figure 3b presents the vegetation degradation scenario for B1, where 90% of the area consists of mixed vegetation cover, while only 10% retains native vegetation. In contrast, 90% of the area of B2 is occupied by pastures, crops, and urban plots, with approximately 10% comprising natural vegetation (Figure 3c). Figure 3d depicts a scenario in which degraded vegetation recovers through urban restoration practices, such as Sustainable Urban Drainage Systems (SUDS) and reforestation with native tree species.

3.3. Hydrological Modeling Under LULC Scenarios

Figure 4 illustrates the hydrological modeling results based on current and future hypothetical land use/land cover (LULC) scenarios. The top panel presents both measured and simulated flows for the selected rainfall events, as well as the current conserved and future degraded LULC scenarios for B1. It is evident that the simulated flows for the current conserved LULC scenario closely follow the trend of the measured flows, with minor overestimates and underestimates. Conversely, the future degraded LULC scenario results in a significant increase in peak flow and a decrease in baseflow. The R^2 coefficient between measured and simulated flows for the current scenario was 0.96, indicating a strong correlation and suggesting that the simulated data closely align with the measured data. This supports the validity of this method for filling in missing data or analyzing events on different dates than those considered in this study.

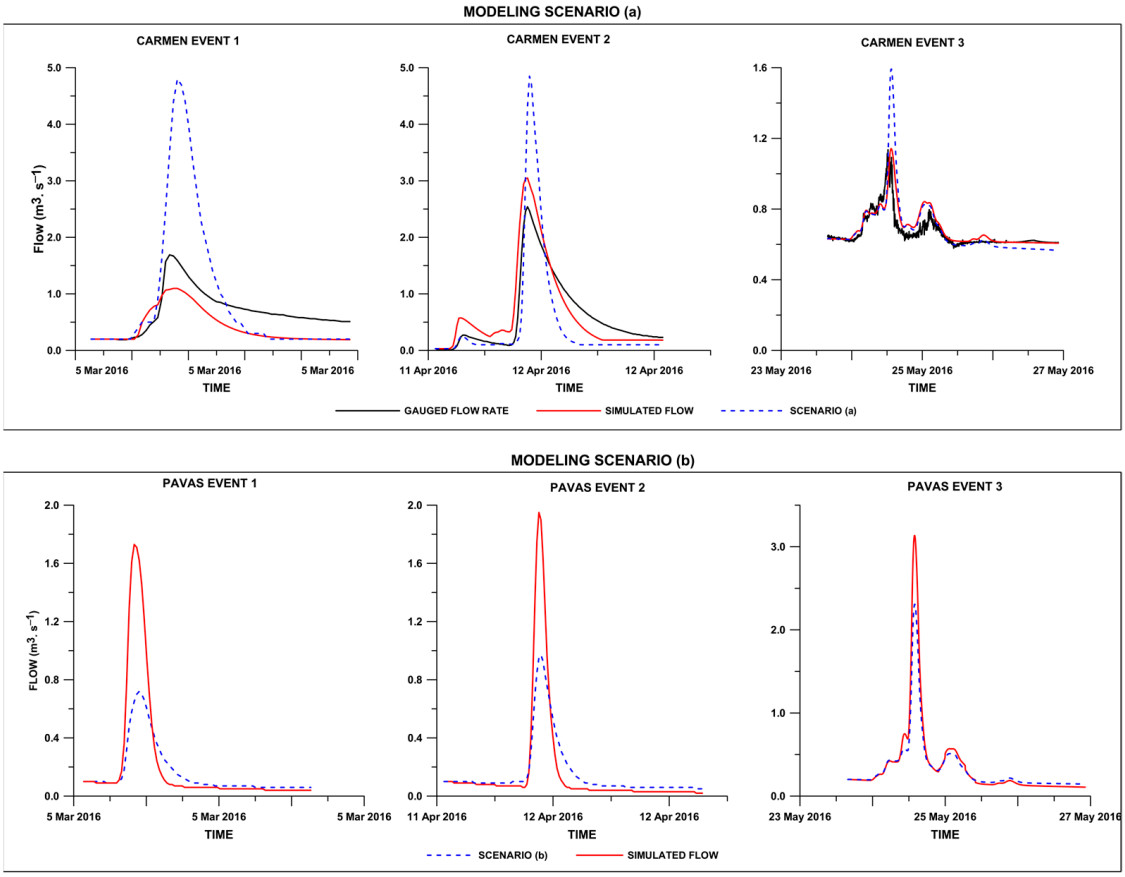

Figure 4. Gauged and simulated flows under the LULC scenarios for basins B1 and B2.

The bottom panel of Figure 4 displays the simulated flows for the current degraded and future restored land use/land cover (LULC) scenarios for B2. In this case, a significant decrease in peak flows and a slight increase in baseflow are observed for the future scenario across all events.

As shown in Table 2, the Nash–Sutcliffe model efficiency coefficient (NSE) values of the hydrological modeling for the current scenario range from satisfactory for events 2 and 3 to unsatisfactory for event 1. Therefore, it can be indicated that the HEC-HMS hydrological model correctly simulates B1, despite the lack of sufficient information.

Table 2. NSE values from hydrological modeling of B1.

Precipitation Event	NSE	
	Current Scenario	Future Scenario
1	0.26 (unsatisfactory)	0.0 (unsatisfactory)
2	0.78 (satisfactory)	0.2 (unsatisfactory)
3	0.67 (satisfactory)	−0.3 (unsatisfactory)

4. Discussion

The hydrological modeling results for two small basins in Loja, Ecuador, demonstrate how vegetation degradation or restoration affect hydrological responses during rainfall events, as previously described in other studies in these basins [21,22].

As shown in Figure 5, for the current scenario in B1 and the future restoration scenario in B2, the results indicate effective hydrological regulation, particularly during intense rainfall events. The vegetated conditions in these scenarios help mitigate flood peaks and support sustained water supply, stabilizing stream flows over time. Conversely, the future scenario in B1 (with vegetation degradation) and the current degraded state in B2 demonstrate rapid hydrological responses, with higher flow peaks occurring over a shorter timeframe and subsequent rapid declines. This pattern increases the likelihood of dry spells, as flows drop to zero more quickly during periods of low water availability. The faster, more intense runoff in degraded vegetation scenarios aligns with findings from Mera et al. (2021), who observed similar behaviors in degraded Andean ecosystems [21]. In B1 (future) and B2 (current), reduced vegetation decreases the soil capacity for infiltration and water storage, leading to greater surface runoff. Consequently, these basins exhibit larger peak flows and diminished baseflow, showing the critical role that intact vegetation plays in hydrological stability.

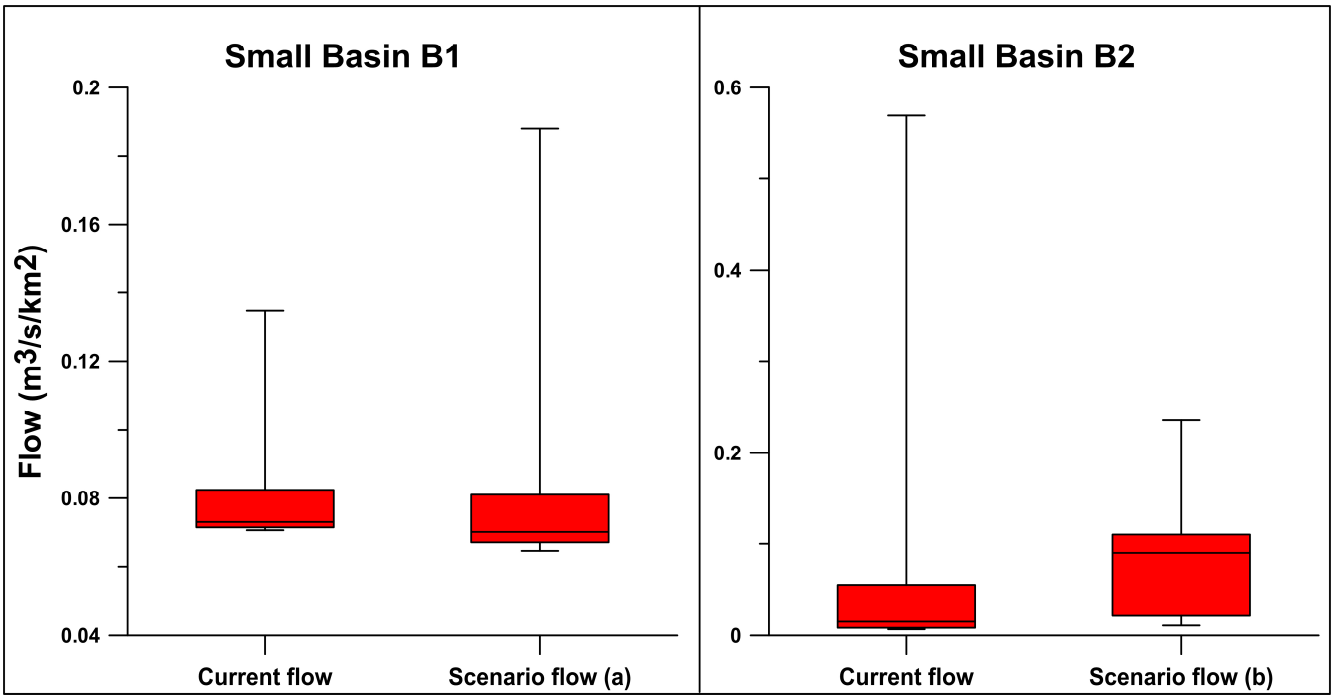

Figure 5. Box plot for scenario-specific flow rates.

This study's findings on vegetation's influence on hydrological regulation are consistent with a broad body of research highlighting the importance of natural vegetation in moderating rainfall interception, infiltration, and water storage [6]. Degraded vegetation, as observed in Loja, accelerates surface runoff and reduces infiltration, resulting in

higher flood peaks and lower baseflows [34,35]. García-Ruiz et al. (2017) documented similar effects in degraded ecosystems, where reduced vegetation cover increases runoff variability, especially during storms, and lessens the ecosystem's capacity to maintain baseflows [36]. Similarly, Bonilla-Bedoya et al. found that Ecuadorian basins that have shifted from natural vegetation to pasturelands exhibit faster hydrological responses to rainfall, leading to more significant flood peaks [19]. Comparable findings have been reported in other mountainous regions, such as southern Canada, where land use changes associated with urban expansion further destabilize hydrological responses in Andean basins [37]. Additionally, studies in Ecuador's small southern basins, like those by Crespo et al., indicate that introducing exotic species (e.g., pine or eucalyptus) in afforestation projects often results in reduced baseflow and diminished capacity for water regulation, aligning with similar observations in Costa Rica [10,38]. These research findings emphasize the need to prioritize vegetation conservation and management strategies to sustain water regulation in mountainous regions.

This study highlights the necessity of including vegetation management in urban planning to maintain the regulation of ecosystems services, especially the water cycle in Loja, mainly in areas susceptible to extreme hydrological events. Strategies like Nature-based Solutions (N-bSs), including Sustainable Urban Drainage Systems (SUDS), along with reforestation using native vegetation, could mitigate flow peaks and improve long-term resilience. For example, prioritizing restoration in the B2 basin, particularly through soil management and riverbank reforestation, could enhance Loja's water security. Integrating these measures into local planning policies, such as Ordinance 3 for environmental protection of small basins in Loja [3,22], would enable the Autonomous Decentralized Government (ADG) to manage water resources more sustainably and mitigate the risks associated with extreme weather events. Monteros et al. (2024) conclude that urban expansion should be planned carefully, considering possible impacts on soil geomorphology and vegetation cover [15], as urban growth substantially affects both water's availability and quality in Andean basins [5,25]. Encouraging reforestation, promoting land use practices that support water infiltration, and establishing green infrastructure are all crucial to maintaining hydrological balance in urbanized Andean areas [21].

While the study offers significant insights, there are notable limitations. The lack of hydrometeorological monitoring, both spatially and temporally, in urban basins such as B2 has generated estimates that are close to reality in this study. But gathering this information is essential for the management of water resources and for decision-making. Also, climate-monitored basins such as B1 are mainly used for academic research purposes and not by government entities such as the municipality of Loja that provides the environmental services of this basin to the local population. Also, this study does not incorporate future climate change scenarios, which could alter the hydrological responses in the basins over extended periods. Additionally, the modeling relies on static vegetation scenarios, which may limit its accuracy for longer projections. Future research could investigate the combined impacts of climate change, urbanization, and vegetation management on hydrological responses, providing a more holistic view of the ecosystem's resilience. Exploring the effects of different native species on reforestation may reveal more nuanced benefits for water yield and flow stability. Addressing these limitations would improve understanding of the interplay between vegetation, climate, and urbanization in Andean basins, informing adaptive planning strategies that enhance water security, ecological integrity, and disaster risk management.

5. Conclusions

The hydrological model used in this study demonstrates significant potential to simulate hydrological behavior under the proposed land use change scenarios. A crucial factor to consider is the weighted curve number in each small basin and a detailed classification of the vegetation cover. Land use changes in these Andean basins generate serious issues for their hydrological balance. For instance, basins with mixed vegetation cover—such as

pastures, crops, and scattered urban areas—tend to exhibit high surface flows, promoting immediate runoff. In terms of base flows, these tend to decrease significantly after short dry periods. Conversely, basins with forested vegetation cover behave differently; they play a vital role in regulating water volume during the summer and preventing large floods during the rainy season. This behavior is particularly crucial in small basins like B1, which supplies a significant water flow to the population of an intermediate city in southern Ecuador.

The results of this study complement existing research and provide a foundation for decision-making. Comprehensive and multidisciplinary studies are necessary to develop public policies at various scales. Additionally, these results offer a general vision for land use planning promoted by the ADG. Specifically, for the city of Loja, it is recommended to review these studies to guide processes and prevent the negative impacts of land use change on the hydrology of its small basins.

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