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Hydrological variability due to changes in land cover in the Wawayme river basin caused by mining activities, Ecuador

Variabilidad hidrológica por cambio de cobertura de suelo en la cuenca del río Wawayme debido a actividades mineras, Ecuador

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Abstract

This study evaluates the hydrological effects resulting from changes in land use and land cover in the Wawayme River basin, Ecuador. The research was conducted through: 1) multitemporal analysis of vegetation cover between 2013 and 2020, using supervised classification with the SCP plugin in QGIS; and 2) comparative hydrological modeling of scenarios for 2015–2020, using the TETIS distributed hydrological model. Hydrological parameters were estimated based on available meteorological data, terrain characteristics, and edaphic properties. As a result, we obtained a decrease of 14.35 % in primary vegetated areas and an increase of 13.86 % in primary non-vegetated areas; and an increase in simulated flow and volume in the basin of 0.002 $m^3\ s^{-1}$ and 0.196 Hm^3, respectively, evidencing a variability in the hydrological behavior of the basin. The limited availability of meteorological and hydrological data is a recurrent challenge in the region. However, the applied methodology highlights the importance of monitoring and managing water resources in areas with extractive activities. This study underlines the need to implement mitigation and conservation measures that minimize environmental impacts and favor the resilience of local communities.

Keywords: Land cover and land use, hydrologic modeling, watershed, mining, environment.

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Resumen

Este estudio evalúa los efectos hidrológicos derivados de cambios en el uso y cobertura del suelo en la cuenca del río Wawayme, Ecuador. La investigación se desarrolló mediante: 1) análisis multitemporal de cobertura vegetal entre 2013-2020 utilizando clasificación supervisada con el plug-in SCP en QGIS; y 2) modelación hidrológica comparativa de escenarios 2015-2020 empleando el modelo hidrológico distribuido TETIS. Los parámetros hidrológicos se estimaron a partir de datos meteorológicos, características del terreno y propiedades edáficas disponibles. Como resultado se obtuvo una disminución de áreas primariamente vegetadas de 14,35 % y un aumento de áreas primariamente no vegetales de 13,86 %; y un aumento del caudal y volumen simulado en la cuenca de 0,002 $m^3\ s^{-1}$ y 0,196 Hm^3 respectivamente, evidenciando una variabilidad en el comportamiento hidrológico de la cuenca. La limitada disponibilidad de datos meteorológicos e hidrológicos constituye un desafío recurrente en la región. No obstante, la metodología aplicada resalta la importancia de monitorear y gestionar de manera adecuada los recursos hídricos en zonas con actividades extractivas. Este estudio subraya la necesidad de implementar medidas de mitigación y conservación que minimicen los impactos ambientales y favorezcan la resiliencia de las comunidades locales.

Palabras clave: Cobertura y uso del suelo, modelación hidrológica, cuenca hidrográfica, minería, ambiente.

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1 Introduction

The global hydrological cycle is undergoing significant modifications as a result of alterations in terrestrial ecosystems. At a global scale, river basins are increasingly facing water availability challenges due to the degradation of their natural conditions. The overexploitation of natural resources, land cover change, and climate change are key drivers reducing both the quantity and availability of water resources, leading to more frequent flood events and increased water stress (Angulo and Saavedra, 2018). Furthermore, it is difficult to conceive of any human activity on land that does not involve soil disturbance or modifications to the upper soil layers, often replacing ecosystems that once contributed to the formation of fertile soils with others that do not (Daily and Ehrlich, 1992).

This ecosystem transformation is particularly relevant in regions characterized by high biodiversity and environmental fragility, such as the Amazon, where alterations in vegetation cover can have significant impacts on regional and local hydrological regimes (Nobre et al., 2016). Recent studies demonstrate that the conversion of natural land covers into anthropized areas can substantially alter runoff, infiltration, and evapotranspiration patterns, thereby generating imbalances in watershed hydrological behavior (Siswanto and Francés, 2019; Fang and Fan, 2021).

Within this context, economic development is often accompanied by activities such as the exploitation of non-renewable resources, particularly mining. In this regard, Ecuador has increased its position as a mining destination by 26 % (Ministerio de Energía y Minas, 2022), reflecting new strategies and regulatory frameworks that mark a shift for a country traditionally reliant on oil and agricultural exports. Major mining projects such as Mirador and Fruta del Norte are currently in operation, while others—including Loma Larga, Curipamba, La Plata, and Cascabel—are expected to enter production in the future (Moreno Farfán, 2022).

Although these developments are consistent with economic growth objectives, it is important to know that mining activities have generated problematic situations due to their inherent impacts (Vásconez and Torres, 2018). Large-scale extractive projects have not been exempted from controversy, particularly regarding concerns over the violation of human rights and the rights of nature (Angelo and Sempere, 2018). This issue becomes especially critical given the location of many of these projects within ecosystems of high ecological value and biodiversity—such as the Ecuadorian Amazon—where inadequate planning and overexploitation of natural resources may lead to severe environmental impacts, particularly affecting water resources.

In recent decades, accelerated soil degradation driven by anthropogenic activities has significantly altered the Earth's surface (de Jong et al., 2021), with nearly three-quarters of it having been modified over the last millennium. At present, addressing global sustainability challenges—such as climate change mitigation, biodiversity loss, and food sovereignty—has become a main concern. These challenges are directly linked to land use and land cover changes, as unsustainable practices can severely affect carbon sources and sinks, lead to habitat loss, and undermine the capacity to sustain food production (Winkler et al., 2021).

Consequently, economic activities such as agriculture, oil extraction, and mining are the main drivers of deforestation in the Ecuadorian Amazon, resulting in biodiversity loss, extensive forest clearing—reaching approximately 50 000 ha $year^{-1}$—and continuous soil degradation (Custode and Sourdat, 1986; Bustamante et al., 1993; Giraldo et al., 2013). For example, in Ecuador, the agricultural and forestry sectors expanded by 45 % over a 37-year period, while mining-affected areas exceeded 7 000 ha by 2021 (Paz, 2024). According to the National Institute of Agricultural Research (INIAP, 2018), soil loss in the country ranges from 30 to 50 t ha^{-1} $year^{-1}$ in foothill areas with slopes greater than 25 %. In areas with slopes between 12 % and 25 %, erosion ranges from 10 to 30 t ha^{-1} $year^{-1}$, while in areas with slopes below 12 %—which comprise much of the Ecuadorian Amazon—erosion is estimated between 5 and 10 t ha^{-1} $year^{-1}$ (Suquilanda, 2008).

Before addressing the relevance of land use and land cover within the hydrological regime, it is essential to define these concepts. Land cover refers to the biophysical surface observed on the Earth, focusing on vegetation and anthropogenic elements.

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Land use, in contrast, is characterized by the arrangements, activities, and inputs undertaken by humans on a given land cover to produce, modify, or maintain it (FAO, 2005).

In a relatively short period, environmental degradation caused by changes in land use and land cover has become a major global concern, attracting increasing attention from researchers. These changes pose a significant threat to watershed sustainability, as they are directly associated with increased water stress, higher frequency of flood events—due to their influence on water supply at the basin scale, where deforestation tends to increase streamflow as a result of reduced evapotranspiration—and alterations in erosion rates and sediment production (Angulo and Saavedra, 2018; Siswanto and Francés, 2019).

Dingman (2014) highlights that vegetation is a key determinant of the hydrological cycle, as it regulates evapotranspiration, infiltration, runoff, interception, and transpiration processes. Vegetation cover plays a fundamental role—alongside precipitation, topography, and other factors—in soil water recharge and runoff formation, directly influencing: (1) net precipitation reaching the soil surface; (2) soil infiltration rates; (3) soil moisture redistribution; and (4) evapotranspiration losses (Pascual, 2002).

Vegetation introduces a bidirectional sub-cycle within the hydrological system due to two main processes: (1) it interferes with the downward flux of precipitation through interception and evaporation losses, modifying the redistribution of fall according to soil infiltration capacity; and (2) it contributes to upward water flux through transpiration, by extracting water stored in soil layers and releasing it into the atmosphere as water vapor (Pascual, 2002).

In summary: (1) vegetation directly influences the water cycle, particularly in the dynamics of water storage surfaces, as it interacts with both the atmosphere and the soil; and (2) as a biological system, it consumes water necessary for its vital functions, forming what Barceló Coll et al. (2000) describe as the soil–vegetation–atmosphere system (Pascual, 2002).

Regarding the role of forests (forest soils and tree cover) in the hydrological cycle, Mintegui Aguirre and Robredo Sánchez (2008) note that they regulate water movement within watersheds by reducing runoff velocity and enhancing infiltration. They also directly influence the horizontal component of the hydrological cycle (transpiration) and interact with precipitation by intercepting vertical rainfall and facilitating the formation of horizontal precipitation processes such as condensation and fog formation.

Additionally, Mintegui Aguirre and Robredo Sánchez (1994) emphasize that: (1) vegetation cover acts as a stabilizing factor in watersheds during extreme rainfall events, mitigating torrential effects and functioning as a natural regulator of water resources; (2) it promotes biological stability and ecosystem regeneration processes, thus playing a conservation role; and (3) it prevents soil loss by reducing the impact of various erosion processes.

In this sense, soils with well-developed vegetation cover maintain sufficient levels of organic matter, improving soil structure and enhancing infiltration capacity. The root systems of forest species create preferential pathways that increase infiltration compared to agricultural soils, thereby contributing more significantly to subsurface runoff (Prats et al., 2011).

According to the FAO, global deforestation rates reached approximately 10 million hectares per year between 2015 and 2020. In Ecuador, the most recent data from the Ministry of Environment, Water and Ecological Transition (2018) indicate an annual loss of approximately 94 353 hectares of forest, a considerable figure compared to other countries in the region (Montaño, 2021). Historically, land use changes in the Amazon have been driven by increasing demand for agricultural products and non-renewable resources (Nobre et al., 2016). Ecuador is no exception, as these activities have been key drivers of deforestation, soil degradation, and the continuous loss of soil resources (Instituto Nacional de Investigaciones Agropecuarias (INIAP), 2018).

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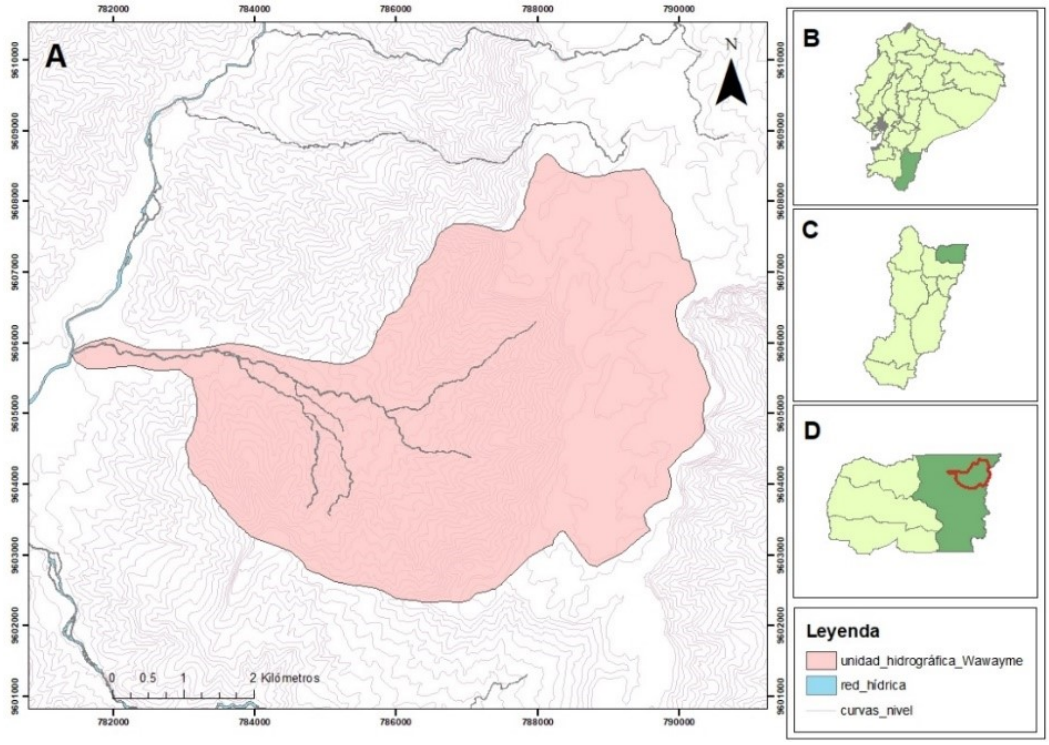


Figure 1. A: Location of the Wawayme River watershed; B: Location of Zamora Chinchipe Province within the Republic of Ecuador; C: Location of El Pangui canton within Zamora Chinchipe Province; and D: Location of the watershed within Tundayme parish, El Pangui canton.

Based on the foregoing, the present study aims to determine the variability in the hydrological balance resulting from changes in land use and land cover within the Wawayme River watershed (Figure 1), located in Zamora Chinchipe Province, Ecuador. This is achieved through geospatial analysis (using the SCP plugin and its post-processing methodology) and hydrological modeling (using the TETIS software). The specific objectives include: (1) quantifying changes in vegetation cover between 2013 and 2020 using remote sensing techniques; (2) implementing a hydrological model to simulate comparative scenarios; and (3) evaluating changes in hydrological regimes associated with the identified alterations in vegetation cover.

2 Materials and Methods

This research adopts a methodological approach that integrates geospatial analysis techniques and hydrological modeling. The methodology is structured into three main components. The first addresses: (1) the climatic and watershed characterization of the study area; (2) the initial operations and methodology used for satellite image classification; and (3) the estimation of TETIS parameters required for the execution of the hydrological model.

2.1 Climatic and Watershed Characterization

Initially, it was considered essential to carry out the climatic characterization of the study area by identifying climatic trends and extreme events, based on data recorded from two conventional meteorological stations located near the study area and operated by the National Institute of Meteorology and Hydrology (INAMHI). It should be noted that these stations are not located within the study watershed; however, they are the closest available (approximately 60 km in a straight line) and provide a more extensive temporal dataset.

The collected precipitation data were processed according to the available temporal scale (monthly

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records from 1990 to 2017), allowing the calculation of Mean Monthly Precipitation values for each station over the available periods. The precipitation regime was identified as bimodal, with peak rainfall occurring between March and July, and lower precipitation during the remaining months of the year.

Further analysis of maximum 24-hour precipitation and the average maximum for each period revealed several years in which values exceeded the average (Figure 2), suggesting that the area has experienced flood events that could potentially recur in future periods.

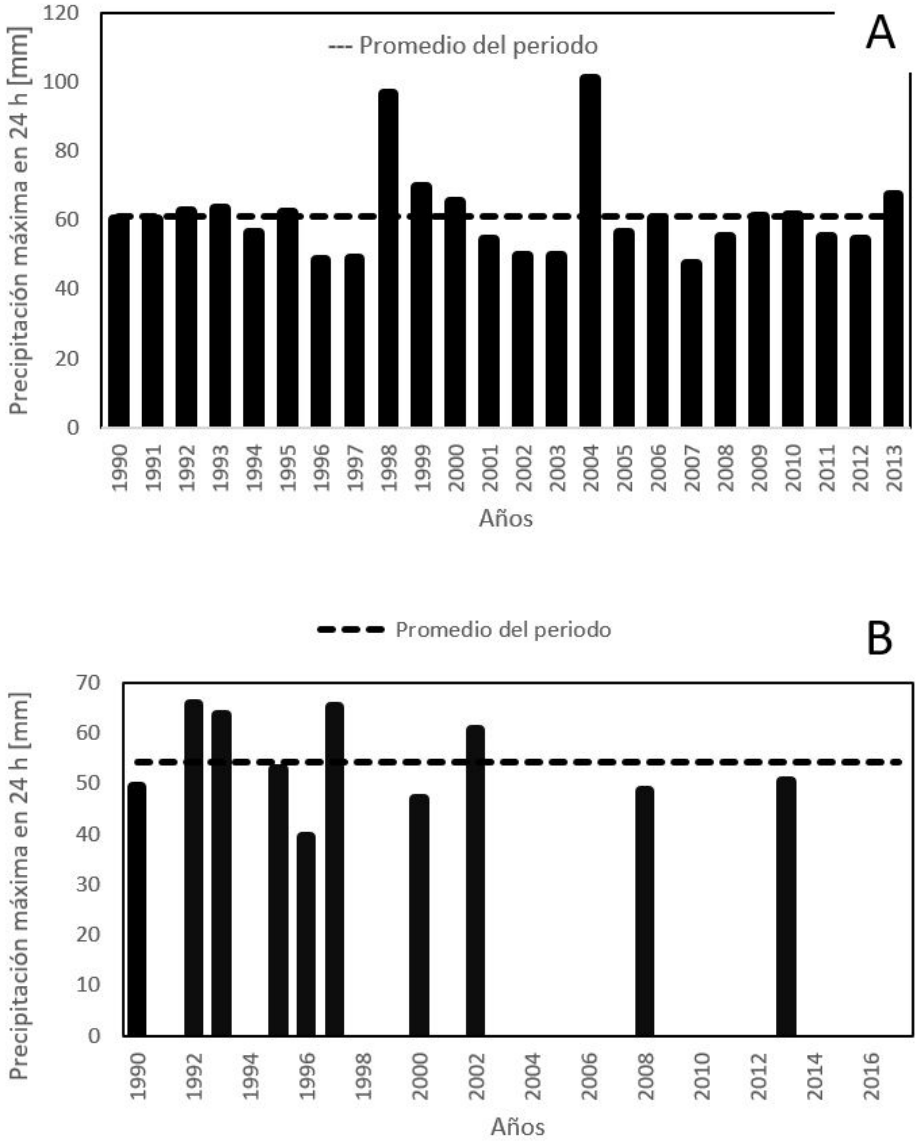


Figure 2. A) Annual maximum 24-hour precipitation recorded at the Gualaquiza meteorological station (INAMHI) for the 1990–2013 period. The dashed line represents the mean value for the study period. Years without bars indicate periods with no available records due to missing data in the INAMHI database. B) Annual maximum 24-hour precipitation recorded at the El Pangui meteorological station (INAMHI) for the 1990–2016 period. The dashed line represents the mean value for the study period. The years 2006 and 2016 are not represented by bars due to the absence of recorded data for those periods. Source: Authors' own elaboration.

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Temperature analysis indicates a mean annual temperature of 23.2 °C, a maximum annual temperature of 28.6 °C, and a minimum annual temperature of 18.11 °C, with the warmest months occurring between October and March. Finally, the analysis of potential evapotranspiration (PET) using the Thornthwaite method yielded an average value of 1 211.65 mm, with higher values observed from October to January.

Regarding the characterization of the Wawayme River watershed, the process begins with the acquisition of a Digital Elevation Model (DEM) (30 × 30 m resolution) downloaded from NASA's Earth Data server (Figure 3), using QGIS software and the SRTM Downloader plugin. Geographic Information Systems (GIS) were employed as the primary tools for data processing and analysis.

The morphometric parameters of the watershed reveal characteristics associated with a moderately torrential hydrological response. In particular, the shape indices (Kc = 1.43; Ff = 0.34) indicate a tendency toward sustained flood generation rather than abrupt responses. In terms of relief, the mean slope (S = 32.12 %) and mean elevation (Hm = 1 648.22 m.a.s.l.) classify the basin as mountainous, which directly influences runoff dynamics and erosion processes. The drainage system exhibits a stream order of 5 and a concentration time (tc = 25.12 min), suggesting that the entire watershed contributes relatively rapidly to runoff processes, thereby favoring the occurrence of peak discharges during intense precipitation events.

Finally, the analysis of the hypsometric curve indicates that the watershed is in a transitional stage between juvenile and mature phases. This is reflected in the altitudinal distribution, where approximately 35 % of the area lies above 1 900 m.a.s.l., suggesting the persistence of active erosive processes. This interpretation is further supported by the altimetric frequency histogram, which shows that the largest proportion of the watershed area is concentrated on the elevation range of 1 900 to 2 080 m.a.s.l.

2.2 Image Classification Methodology

For analyzing changes in vegetation cover, a supervised classification methodology was implemented using the Semi-Automatic Classification Plugin (SCP) in QGIS. This approach enables the identification and quantification of land cover transformations based on multitemporal satellite imagery. Initially, two complete Landsat 8 images dated April 27, 2013, and September 12, 2020—covering southern Ecuador and northern Peru—were used. These images were downloaded from the United States Geological Survey (USGS) Earth Explorer portal and include nine bands from the Operational Land Imager (OLI) sensor and two bands from the Thermal Infrared Sensor (TIRS).

It is important to note that the images correspond to Level 1T (L1T) products, meaning that they have undergone systematic radiometric correction, as well as orthorectification and terrain correction.

Table 1. Data set showing the monthly variation in evapotranspiration across four types of vegetation cover.

Code	Land Use	January	February	March	April	May	June	July	August	September	October	November	December	Interception
1	Native forest	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	4.00
2	Shrub vegetation	0.70	0.70	0.75	0.88	0.98	0.95	0.75	0.70	0.70	0.70	0.70	0.70	0.00
3	Grasslands	0.40	0.40	0.50	0.75	0.95	0.90	0.50	0.40	0.40	0.40	0.40	0.40	5.00
4	Anthropogenic infrastructure	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	1.00

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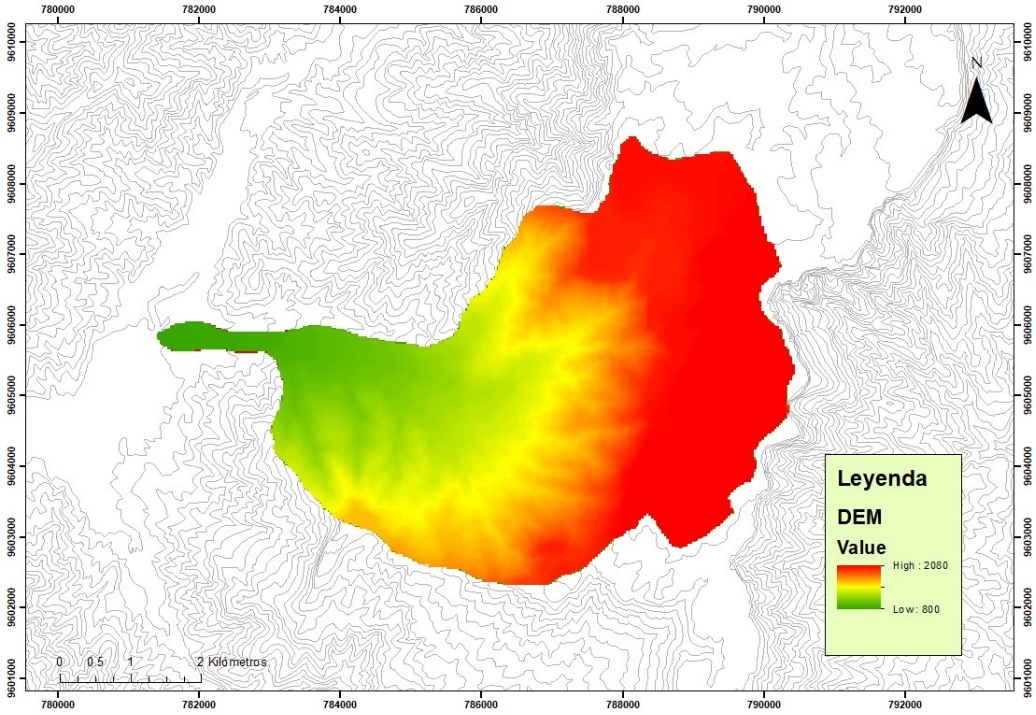


Figure 3. Digital Elevation Model of the Wawayme River watershed

Subsequently, using the Semi-Automatic Classification Plugin (SCP) in QGIS and through the combination of spectral bands, land cover changes within the study area were quantified, including the application of preprocessing steps prior to classification. For this study, the (FAO, 2005) classification system was adopted, which includes distinctions at three levels (primary, secondary, and tertiary). The primary level is particularly relevant for this research, as it establishes a dichotomous classification to determine the presence or absence of vegetation (Table 1).

2.3 Hydrological Modeling

To evaluate the influence of land cover changes on hydrological response, the TETIS model was implemented. This is a distributed conceptual model that allows the simulation of watershed behavior under different land use scenarios. The modeling process included parameterization, calibration, and validation stages.

The TETIS model, developed by the Department of Hydraulic Engineering and Environment at the Polytechnic University of Valencia, is a rainfall–runoff tank-type model that maintains water balance in each grid cell of the system. Its structure enables the integrated representation of hydrological processes such as interception, surface storage, infiltration, evapotranspiration, percolation, and groundwater recharge, among others (Instituto de Ingeniería del Agua y Medio Ambiente (IIAMA), 2021). Furthermore, this model can be applied both to the analysis of extreme events—such as floods and erosion processes—using minute or hourly time steps, and to water resource availability studies at a daily scale, making it a versatile tool for hydrological simulation in watersheds.

According to Barrientos et al. (2020), the model can analyze changes in watershed runoff by considering the effects of intensive forestry and/or climate change through the simulation of different land use and climate scenarios. Their findings indicate that runoff can be significantly influenced by reductions in precipitation and increases in evapotranspiration.

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In this regard, Rodríguez-Lloveras et al. (2015) highlight that this approach allows for the estimation of runoff rates and sediment yield based on historical changes in land use and vegetation, concluding that land management and land use are decisive factors in watershed hydrological behavior, particularly in relation to erosion and sediment yield. Additionally, appropriate land use management can mitigate the adverse impacts of climate change on the hydrological cycle (Fang and Fan, 2021).

TETIS requires a set of initial parameters, which can be grouped into: (1) parameters derived from the DEM (elevation, slope, flow direction, flow accumulation, and hill slope velocity); (2) parameters derived from edaphic, hydrogeological, and geomorphological properties (static storage, infiltration capacity, percolation capacity, among others); and (3) parameters derived from land use and land cover.

The first raster input for the hydrological model is the Digital Elevation Model (DEM). In this study, a DEM (30 $\times$ 30 m resolution) previously downloaded from NASA's Earth Explorer server (Figure 3) was used. It is important to note that, after acquisition, surface imperfections were corrected using the "Fill sinks" tool. From this dataset, slope, flow direction, flow accumulation, and hill slope velocity layers were derived.

Parameters derived from edaphic, hydrogeological, and geomorphological properties include: (1) static storage, referring to water within the watershed that is lost through evapotranspiration and does not contribute to runoff; (2) infiltration capacity, defined as the rate at which water enters the soil through its surface and dependent on the different soil types present in the watershed; and (3) percolation capacity, referring to the downward movement of water through the soil toward the aquifer via the unsaturated zone, associated with subsurface structure and geological and geomorphological characteristics.

These parameters were estimated as a function of altitude (empirical relationship), due to the absence of observed data for watershed, following the methodology proposed by Terán (2017). For example, static storage values were estimated at approximately 200 mm at 5 000 m.a.s.l., and around 350 mm at 2 000 m.a.s.l.

The land cover dataset was derived from the geopedological database of the project "Thematic Cartography Survey at 1:25,000 Scale, Lots 1 and 2," conducted by the Ministry of Agriculture and Livestock (MAG) through the MAGAP-PRAT executing unit within the SIGTIERRAS program (2015) (Figure 4A), as well as from the Landsat 8 image dated September 12, 2020 (Figure 4B). Four land cover types were identified within the watershed: (1) native forest; (2) shrub vegetation; (3) grasslands; and (4) anthropogenic infrastructure.

Another input required by the TETIS model corresponds to the temporal variation of evapotranspiration, which includes the month-to-month variation for each vegetation cover type present in the watershed. This data set consists of thirteen columns: the first column corresponds to January values, the twelfth to December, and each row represents a specific vegetation cover type identified within the basin.

Due to the absence of monthly values for the vegetation factor in the present study, reference values from similar vegetation covers were adopted, following the FAO methodology and the study conducted by Tejada Espinoza (2016) in the implementation of the TETIS model in the Carraixet ravine watershed (Table 1).

Regarding the event file, this input corresponds to precipitation, evaporation, and discharge data, representing a rainfall event over a specific period. For the present study, monthly data derived from the meteorological and hydrological station described in the section on climatic and watershed characterization were used, covering the period from February 2012 to June 2015.

Finally, within the modeling process, it is necessary to perform a calibration (using the previously described data files), which aims to achieve a closer approximation to reality by adjusting and combining parameters. In this stage, the objective was to obtain appropriate values for each evaluation criterion (RMSE and Nash–Sutcliffe efficiency), as well as to improve the fit between the peak flows of the hydrograph.

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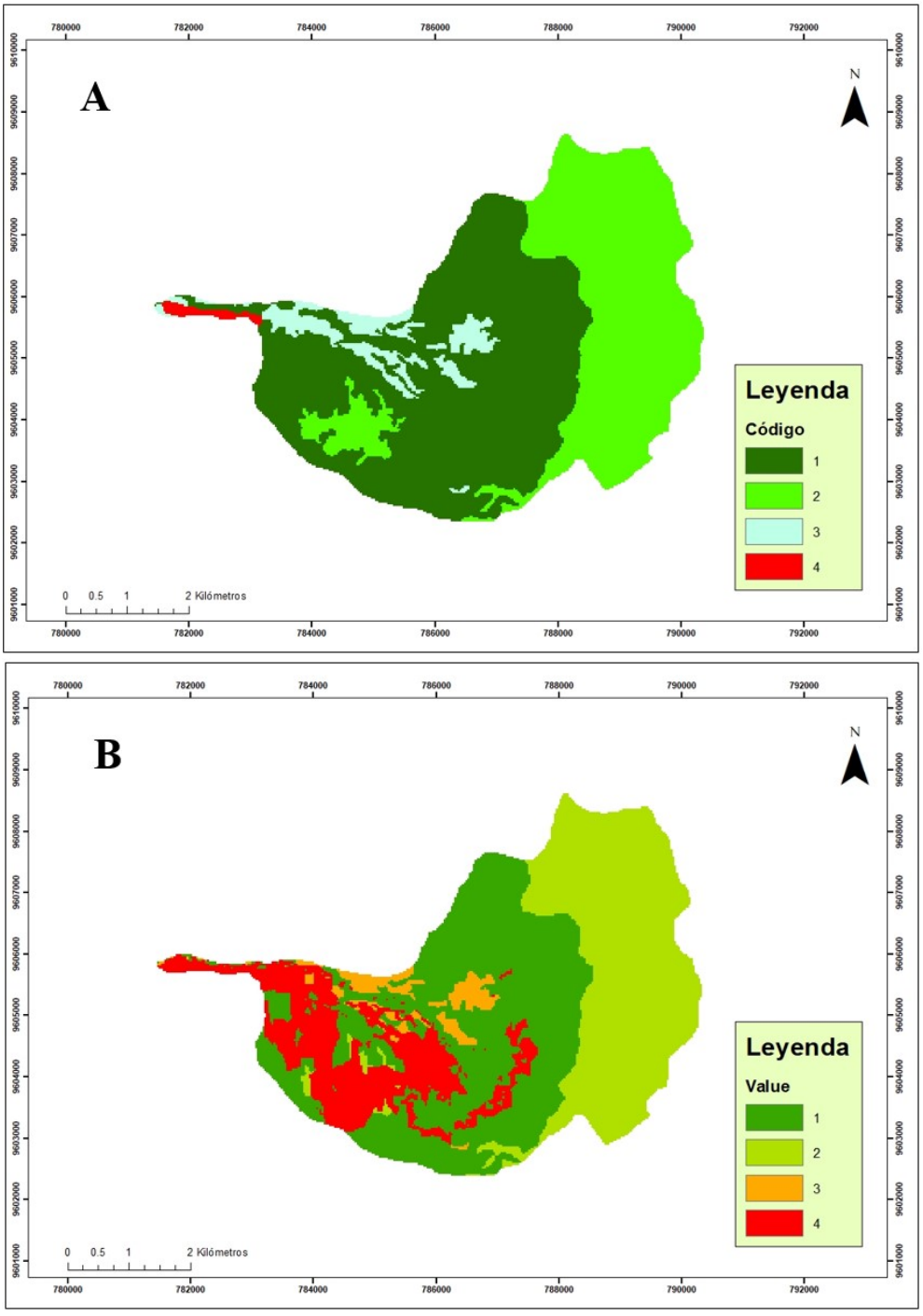


Figure 4. A) Land cover map for 2015, derived from the geopedological database of the SIGTIERRAS Project – MAG (2015). B) Land cover map for 2020, obtained through supervised classification of a Landsat 8 image. In both maps, the colors represent the following land cover classes: code 1 (dark green) = native forest; code 2 (light green) = shrub vegetation; code 3 (orange/light blue) = grasslands; and code 4 (red) = anthropogenic infrastructure. Since monthly values for the vegetation factor were not available, values from similar vegetation cover types were adopted following the methodology proposed by the Food and Agriculture Organization (FAO) and the study conducted by Tejada Espinoza (2016) on the implementation of the TETIS model in the Carraixet Ravine watershed (Table 1).

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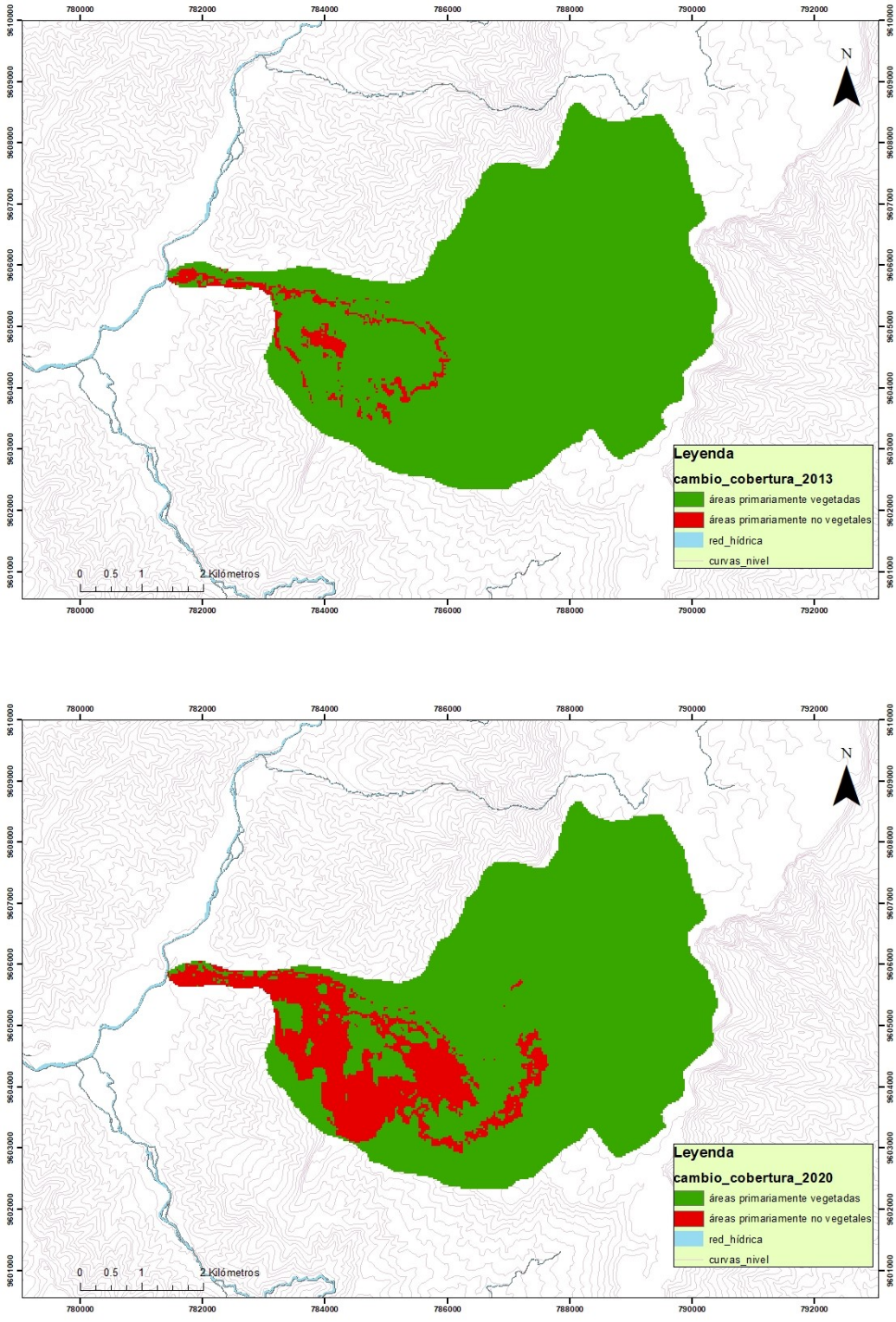


Figure 5. Land cover classification for the years 2013 and 2020.

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3 Results and Discussion

This section presents the results of: (1) the assessment of land cover change in the Wawayme River watershed; (2) the hydrological modeling, in which observed and simulated discharges are obtained as a function of land use and land cover changes; and (3) the discussion of the findings of this study.

3.1 Results of Land Cover Change Assessment

The analysis began with two classifications based on satellite images corresponding to the years 2013 and 2020. The 2013 classification was used as the reference image, while the 2020 classification represented the updated scenario. This process was carried out using the SCP plugin and its post-processing method (land cover), which enabled the calculation of the number of pixels transitioning from one class to another.

The results show a decrease in primarily vegetated areas (PVA) from 28.43 km^2 in 2013 to 24.34 km^2 in 2020, representing a loss of 14.35 %. Conversely, primarily non-vegetated areas (PNVA) increased from 1 km^2 in 2013 to 5.08 km^2 in 2020, corresponding to an increase of 13.86 % (Table 2, Figure 5).

Additionally, Figure 7 presents a multitemporal comparison that more clearly illustrates the land use and land cover changes occurring within the watershed. The analysis of land cover changes reveals a significant transformation of the landscape, where areas of native vegetation are being primarily replaced by mining infrastructure and degraded lands. This transition represents a concerning pattern from an ecological perspective, as primary vegetation performs critical hydrological functions that are now being compromised.

Table 2. Land use and land cover change analysis in the Wawayme River watershed, years 2013 and 2020.

New \ Reference	**Primarily Vegetated Areas (PVA)**	**Primarily Non-Vegetated Areas (PNVA)**	**TOTAL 2013**
Primarily Vegetated Areas (PVA)	24.21	4.22	28.43
Primarily Non-Vegetated Areas (PNVA)	0.14	0.86	1.00
TOTAL 2020	24.34	5.08	29.42

3.2 Hydrological Modeling

It is well established that distributed hydrological models are useful for simulating scenarios that determine the influence of specific parameters. In this research the main objective is to assess the influence of land use and land cover changes on discharge at the gauging point.

The hydrographs resulting from the simulations for the years 2015 and 2020 show variations in simulated discharge ($m^3\ s^{-1}$) and simulated volume (Hm^3) over a period of 43 800 minutes (monthly data) (Figure 6). The results indicate: (1) a maximum observed discharge of 5.6 $m^3\ s^{-1}$ and an observed volume of 217.4 Hm^3 (for both scenarios); (2) a maximum simulated discharge of 5.7 $m^3\ s^{-1}$ for both the 2015 and 2020 scenarios; (3) simulated volumes of 186.5 Hm^3 (2015 scenario) and 186.7 Hm^3 (2020 scenario); and (4) an RMSE value of 1.01 and a Nash–Sutcliffe efficiency index of 0.03 (for both scenarios) (Table 3).

The Root Mean Square Error (RMSE) allows quantifying the magnitude of the deviation between simulated and observed values, ranging from zero to positive infinity. A value of zero indicates a perfect fit, whereas larger values reflect a poorer model performance. For both simulations, an RMSE value of 1.009 was obtained, which represents an adequate level of agreement (Cabrera, 2012).

Regarding the Nash–Sutcliffe efficiency criterion—one of the most widely used metrics in hydrology—it measures how much of the variability in the observed data is captured by the simulation. For both scenarios, a value of 0.0350 was obtained,

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which is close to the mean benchmark value (E = 0). Additionally, during model calibration, efforts were made to improve the fit of the peak flows in the hydrograph, which influenced the resulting Nash–Sutcliffe efficiency value (Cabrera, 2012).

One of the conditions highlighted by the results in relation to determining greater variability in the hydrological balance due to changes in land use and land cover is the limited availability of meteorological and hydrological data—a recurrent issue in Ecuador, particularly in Amazonian watersheds. For the present study, a design was implemented in which variability in simulated discharges and volumes is observed, showing an increase in maximum simulated discharge of 0.002 $m^3\ s^{-1}$ and 0.196 Hm^3 in simulated volume when comparing the 2020 scenario with that of 2015.

In the case of an applied hydrological study, a larger amount of hydrological data and greater temporal resolution (e.g., daily values) over at least one complete hydrological cycle would be required. This should include information on precipitation, stream flow measurements, evapotranspiration, among others, to determine the hydrological behavior of the watershed more accurately.

Additionally, field-based data on the initial parameters required by the model such as static storage, infiltration capacity, and percolation would be necessary.

3.3 Discussion

Given the differences observed between discharge and volume increases obtained from the respective model simulations, it is evident that the watershed exhibits variability in its hydrological characteristics, derived from spatial changes in land use and land cover (Figure 4). This information is relevant due to: (1) the environmental risk associated with the reduction of vegetated areas and the consequent increase in stream flow in natural channels due to decreased evapotranspiration; (2) the occurrence of marked flood events; (3) the intensification of water deficit; and (4) the need for ecosystem conservation and erosion control.

In this context, based on the findings of the present study and the provisions outlined in the National Climate Change Adaptation Plan of Ecuador (2023–2027) (MAATE, 2023), it is imperative to improve monitoring, data management, and access to hydrological and water-related information. This would enhance the resilience of populations located within the direct and indirect areas of influence of extractive projects, as well as reduce the risk of economic losses associated with climate variability. Understanding and predicting the factors that modulate such variations requires strengthening, expanding, and improving hydrological and meteorological monitoring, as well as data management and accessibility. This may be achieved through actions such as equipment acquisition, the implementation of strategic action plans, and the development of policies related to the collection, management, and exchange of climate information in the short, medium, and long term.

Furthermore, it is essential to establish inclusive and transparent governance in water resource management, involving all stakeholders to implement mitigation and conservation measures addressing environmental risks associated with such activities, while also strengthening community resilience.

It is important to note that, given the limitations in input data (monthly records, distant meteorological stations, and estimated soil parameters), the absolute discharge values should be interpreted with caution. The associated uncertainty is estimated at $\pm$20–30 % (Beven, 2012). Therefore, the main contribution of this study lies in the relative comparison between scenarios (a change of +0.02 $m^3\ s^{-1}$ between 2015 and 2020), rather than in the absolute modeled values. Although this difference is small in absolute terms, it represents an increase that could be amplified during periods of higher precipitation.

Finally, while the analysis of vegetation cover change using remote sensing constitutes the most robust component of this study (due to its objectivity and replicability), hydrological modeling—despite its limitations—serves the purpose of translating these spatial changes into projected hydrological consequences. The model results should be interpreted as indicators of trends (i.e., direction of change) rather than precise predictions. Nevertheless, the methodology presented is replicable and can be improved as higher-quality input data become available.

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Table 3. Results. A: Simulation corresponding to the year 2015; B: Simulation corresponding to the year 2020.

A			B		
Description	**Value**	**Unit**	**Description**	**Value**	**Unit**
Maximum observed discharge	5.6	$m^3\ s^{-1}$	Maximum observed discharge	5.6	$m^3\ s^{-1}$
Maximum simulated discharge	5.7	$m^3\ s^{-1}$	Maximum simulated discharge	5.7	$m^3\ s^{-1}$
RMSE	1.010		RMSE	1.010	
Observed volume	217.4	Hm^3	Observed volume	217.4	Hm^3
Simulated volume	186.5	Hm^3	Simulated volume	186.7	Hm^3
Nash–Sutcliffe Efficiency (NSE)	0.035		Nash–Sutcliffe Efficiency (NSE)	0.035	
Accumulated area	23.909	km^2	Accumulated area	23.909	km^2

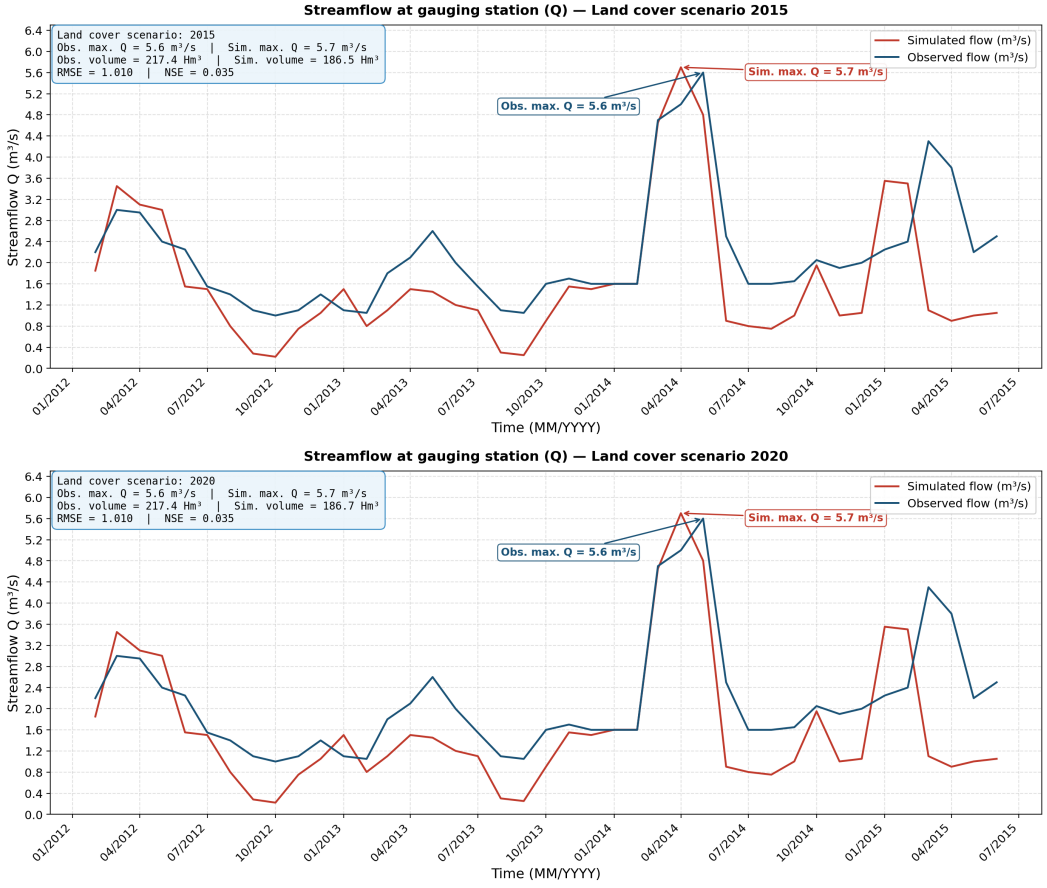
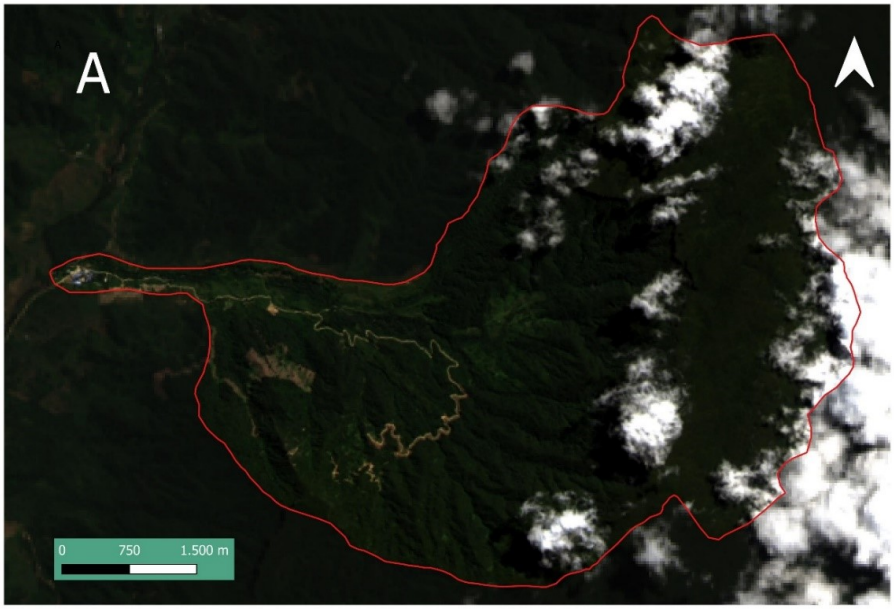
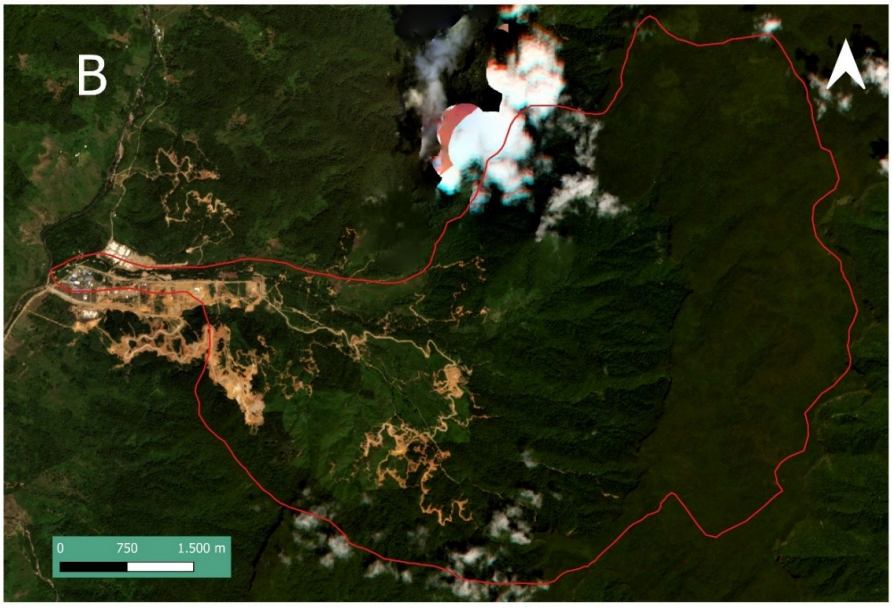


Figure 6. Hydrological charts resulting from the simulations for the years 2015 and 2020

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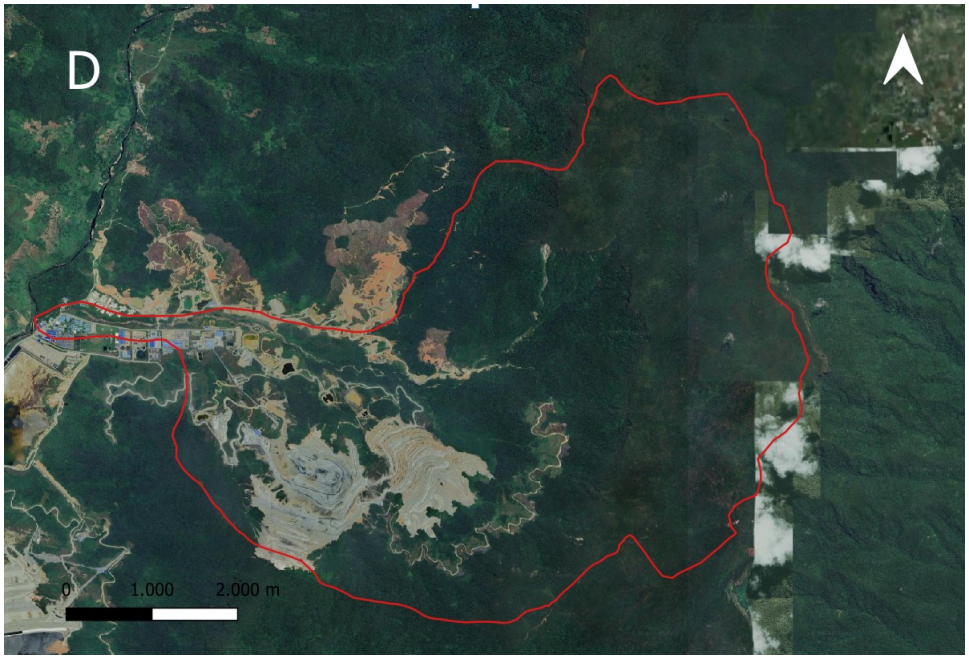


Figure 7. A (2013): The watershed was predominantly covered by dense vegetation, with only minimal anthropogenic disturbance observed at its western edge. B (2015): Areas of bare soil became clearly visible in the central-western sector. Mining infrastructure was evident along the western margin, indicating the onset of significant land disturbance. C (2020): A substantial expansion of the disturbed area was observed. An open-pit mine was clearly identifiable in the central part of the watershed, characterized by extensive exposed soil. Mining infrastructure had become well established along the western margin, while green vegetation remained predominant in the eastern sector. D (2025): The open-pit mine dominated the central-southern portion of the watershed, with well-defined extraction benches clearly visible. Degraded areas had expanded northward across the basin. Although the eastern sector retained forest cover, increasing anthropogenic pressure was evident.

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4 Conclusions

The implementation of the distributed conceptual hydrological simulation model TETIS allows identifying the variability in the hydrological balance as a function of changes in land use and land cover. Specifically, an increase in maximum discharge and simulated volume of 0.002 $m^3\ s^{-1}$ and 0.196 Hm^3, respectively, was determined when comparing the scenarios for the years 2015 and 2020. Furthermore, model calibration enabled a better fit between observed and simulated data series—particularly in achieving an appropriate adjustment of peak flows in the hydrographs—yielding satisfactory results for the RMSE and Nash–Sutcliffe objective functions.

By applying the FAO (2005) classification system through the SCP plugin and its post-processing methodology, land cover changes in the watershed were assessed. The results indicate a decrease of 14.35 % in primarily vegetated areas and an increase of 13.86 % in primarily non-vegetated areas between 2013 and 2020, as evidenced by the corresponding multitemporal comparison.

Consequently, considering that the watershed is located within unique ecosystems of high biological diversity (Ecuadorian Amazon region), it is essential to implement adequate extractive management practices. A lack of planning and the overexploitation of natural resources may lead to severe environmental alterations, particularly affecting water resources. Therefore, the applied methodology highlights the issues associated with the reduction in vegetation cover, reflected partly through hydrological variability.

Likewise, it is important to evaluate the effectiveness of current regulatory frameworks for watershed protection in mining areas of Ecuador, and to propose improvements based on scientific evidence as part of public policy strategies in the region. In this sense, this research serves as a starting point from which appropriate measures should be developed to minimize risks associated with flood events and their environmental impacts.

Finally, future research lines are proposed as follows: (1) the implementation of high temporal resolution hydrometeorological monitoring networks within the watershed; (2) the evaluation of the effectiveness of mitigation measures implemented by the mining project; (3) the development of water quality studies to complement the quantitative analysis; (4) the extension of the analysis to other Amazonian watersheds with similar mining activities; and (5) the development of predictive models incorporating climate change scenarios.

Declaration on the use of artificial intelligence

The authors DECLARE that, during the preparation of the article entitled "Hydrological Variability Due to Land Cover Change in the Wawayme River Basin Associated with Mining Activities, Ecuador", no generative artificial intelligence tools or automated assistance systems were used for the writing, analysis, data interpretation, content generation, translation, or editing of the manuscript.

The authors assume full responsibility for the content, originality, integrity, and final version of the article.

Author's contribution

R.A.M.F.: Conceptualization, formal analysis, investigation, methodology, resources, software, visualization, writing – original draft. **M.Z.F.L.:** Investigation, supervision, validation, writing – review and editing.

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